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EXPERIMENTS EVALUATING COMPLIANCE AND FORCE FEEDBACK EFFECT ON MANIPULATOR PERFORMANCE

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GENERAL ELECTRIC

EXPERIMENTS EVALUATING COMPLIANCE

AND FORCE FEEDBACK EFFECT ON

MANIPULATOR PERFORMANCE

FINAL REPORT

Prepared For:

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SECTION 1

ABSTRACT

The objective was to assess the performance capability of operators performing simulated space tasks using manipulator systems which had compliance and force feedback varied. Two manipulators were used, the E-2 electromechanical man-equivalent (force, reach, etc.) master-slave system and a modified CAM 1400 hydraulic master-slave with 100 lbs. force capability at reaches of 24 ft. The CAM 1400 was further modified during this contract to operate without its normal force feedback.

Several experiments and simulations were performed. The first two involved the E-2 absorbing the energy of a moving mass and secondly, guiding a mass thru a maze. Thus, both work and self paced tasks were studied as servo compliance was varied. Three simulations were run with the E-2 mounted on the CAM 1400 to evaluate the concept of a dexterous manipulator as an end effector of a boom-manipulator. Finally, the CAM 1400 performed a maze test and also simulated the capture of a large mass as the servo compliance was varied and with force feedback included and removed.

It was concluded that large changes in compliance had a discernable effect on task performances but that the degradation of performance with increases in compliance was relatively small. Thus, larger compliances for space boom designs are not ruled out by this work although precautions must be considered. The necessity of force feedback in manually operated large manipulators was confirmed. The dexterous end effector simulations provided little definite and concisive results due to limited numbers of simulations performed.

SECTION 2

SUMMARY

2.1 Study Objectives:

Because there is considerable interest in the concept of manipulator
systems for space applications such as the Shuttle, Space Station, and free
flying teleoperator, this study was undertaken to gather data on the performance
of manipulator systems with and without force feedback and with varying amounts
of system compliance. Compared to manipulator systems designed for earth use,
manipulator systems designed for use in space will be lighter weight and
constrained in size, therefore resulting in more flexible or compliant designs.
Manipulator systems are either bilateral (force feedback) or unilateral (no
force feedback). Bilateral systems compared to unilateral systems are more
complex, costlier, and heavier. The objective of this study was to determine
the affects of compliance and force feedback on the ability to do various
tasks with several operators.

2.2 Equipment Used

By use of the presently available equipment owned by NASA/MSC and the
General Electric Company, it was possible to begin to gather data quickly and
rather inexpensively. NASA/MSC had already purchased a modified General
Electric industrial master/slave manipulator (the CAM 1400 model) and has
mounted this system next to an epoxy air bearing floor in Bldg. #13 as is
shown in Figure 2-1. The CAM 1400 was modified by: increasing the boom
lengths to 12 x 13 ft., the longest boom of this size built; removing the
master station for remote operation (ordinarily the operator rides in azimuth
with the boom); and adding two end effector motions, pitch and yaw, the first
of which maintains its attitude relative to the ground plane by a servo control.
The operation of the slave boom is by a bilateral master/slave control, i.e.,

it duplicates in three degrees of freedom the motions of the operator's arm and feeds back to the operator a fraction of the applied and inertia forces.

One of the end products of this contract was to modify the CAM 1400 for non-force feedback operation. This was accomplished, and it is now possible for one engineer to switch the boom from bilateral to unilateral control or vice versa in less than two hours. To study changes in compliance, one would ordinarily consider changing the stiffness of the boom segments. This would be relatively costly and so a compromise was selected. At lower servo gains, the manipulator joints would need more deflection to apply the same torques. That is, if the boom were being rigidly held extended at the master and the servo gain lowered, the end of the slave would droop or deflect more for the same load. Then the boom appears more compliant. To the operator who just watches the end of the boom, the effect is the same as replacing the boom by less stiff segments. It should be strongly kept in mind, however, that the boom appears to the operator strongly over-damped and lowering the gain in- creases the effective damping. Thus, the compliance changes by servo adjust- ment causes the operator to apply more or less motion to the master, but does not model an under-damped boom where oscillations would be noticeable.

The E-2 electromechanical master/slave manipulator owned by General Electric was also used in these experiments. It is shown in figure 2-2. It is a bilateral man-equivalent manipulator with a nominal 6 lb. force capability. Its upper arm is 18 inches and the forearm 30 inches. The wrist and tong motions are all cable driven, giving a narrow profile to the wrist and forearm. This manipulator was used in some of the tests for several reasons. First, its servo compliance was easily adjustable thru a broader spectrum than possible on the CAM 1400. Force feedback was also removeable but now at the flick of a switch. Finally, it made possible several simulations involving a dexterous man-equivalent manipulator on the end of a larger boom manipulator.

2.3 Description of Experiment:

The study began with experiments using the E-2, since time was required to make the electronic cards which would allow changes to the CAM 1400. The two tasks originally envisioned were mass catching and mass positioning. The former would be a work paced task analogous to capture of satellites in space, while the later would be analogous to position of payloads in and out of the shuttle at the operator's own pace.

These tests would then be repeated but on a larger scale by using the CAM 1400. In between thest two series of tests were run the simulation of the dexterous end effector. The subjects used in all the tests were NASA/MSC engineers who were involved in the space manipulator program.

1. E-2 Pendulum Catching: To control the variables, a simple pendulum test was devised. Use of the 33 foot pendulum with its easily controlled energy and path precluded variations due to different amounts of energy to be absorbed or task time variations because of differences in the subjects catching ability. Each subject then caught the same 400 lb. mass at the same position and velocity and brought the mass to rest as quickly as possible. The main dependent variable was the servo compliance which was changed in four steps by over an order of magnitude. Data was collected by a strip chart recorder which showed the pendulum position and E-2 motor voltages as a function of time.

2. E-2 Maze Test: A 650 lb. mass suported by two airpads was guided thru a maze pattern lying in the horizontal plane. The E-2 gripped the mass above the c.g. on the 5/8 inch O.D. pipe which also acted as the air supply. The subject sat immediately next to the maze and directed the movement of the mass thru the maze by applying appropriate master motions. It was originally intended for the subjects to restrain their

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speed so that all contact would be avoided. During the tests, since the learning curve appeared to be rather lengthy and data not consistent enough, the subjects were told to go as fast as possible yet avoid contact, i.e., the emphasis shifted from accuracy to speed. The data consisted of the task time and number of errors (wall contact).

3. E-2 As Dexterous End Effector: There were three types of simulations involving the E-2 as the CAM 1400 end effector. The first simulated satellite capture, the second satellite inspection, and the third – satellite repair. There were also three locations for the TV cameras besides doing the simulations by direct viewing. The simulations involved either a single operator or two operators. The subject's qualatative comments were the primary data source, although video tapes were also taken of various runs.

4. CAM 1400 Tests: The maze test was repeated but at a 4:1 scale up in size and an increase to 7,000 lbs. The compliance could not be as greatly varied as with the E-2. Only two compliance settings were used. It was noticed that not enough data points were taken with the E-2 maze test, so during this test the full learning curve was explored. The maze test was tried without force feedback on the CAM 1400 but not enough runs were completed to arrive at a quantitative comparison. The final test involved capturing the 7,000 lb. mass as it was moving past the boom. The mass was pushed by hand at velocities between 1/2 and 3 fps. The boom essentially grabbed the mass, using only three degrees of freedom. Again, compliance was varied and some runs made without force feedback.

2.4 Results:

The E-2 pendulum test showed a measurable increase in task times with increase in compliance. However, the task time only went from 4.64 seconds to 5.47 seconds as the compliance increased from about .15 in/lb. to 1.8 in/lbs. Although this is a small percentage increase, if one considers that the 4.64 sec. time approaches the theoretical minimum time with the given E-2 force level, the increase appears more significant.

The E-2 maze test results are clouded by the fact that apparently not enough data was taken. The subjects were still learning in many cases. However, careful analysis of the data predicted longer times when learning would have been complete with increase in compliance, but the increase would be small. The percent increase seems to be less than that of the pendulum test. Again, the subjects came close to the theoretical minimum task time.

The CAM 1400 maze test data was sufficient to show definite results. The two compliance settings (a 5:1 change) had differences in time of a little more than 1/2 second. Low compliance runs averaged 17.91 and 16.61 seconds in the clockwise and counter-clockwise direction respectively, while the higher compliance runs averaged 18.46 and 17.23 seconds. Thus, the different direction was much more significant than the change in compliance. For some of the subjects, it would be difficult to tell from the learning curve plots when the compliance changes were made. Attempts to do the maze task without force feedback were extremely difficult. It was evident that the task was much more difficult as the best time is 40 seconds, which is three times that of the better force feedback runs. Also, none of the non-force feedback runs have been done with less than three errors, whereas about 50% of the runs were successful (one or no errors) with force feedback.

The capture of the satellite simulation showed captures up to 2.8 fps and 100% success below 1.0 fps when force feedback was used. Without it the successful capture ratio dropped off to about 50% below 1 fps. However, there was really not enough data to come to any definite quantitative answer.

The dexterous end effector simulation showed the concept to be capable of the tasks assigned, but also left the impression that future designs would need a fully integrated design. There were differences of opinion on many questions and the runs were treated as preliminary in nature. More detailed or quantitative results were left for later simulations where the tasks and equipment designs could be made more realistic.
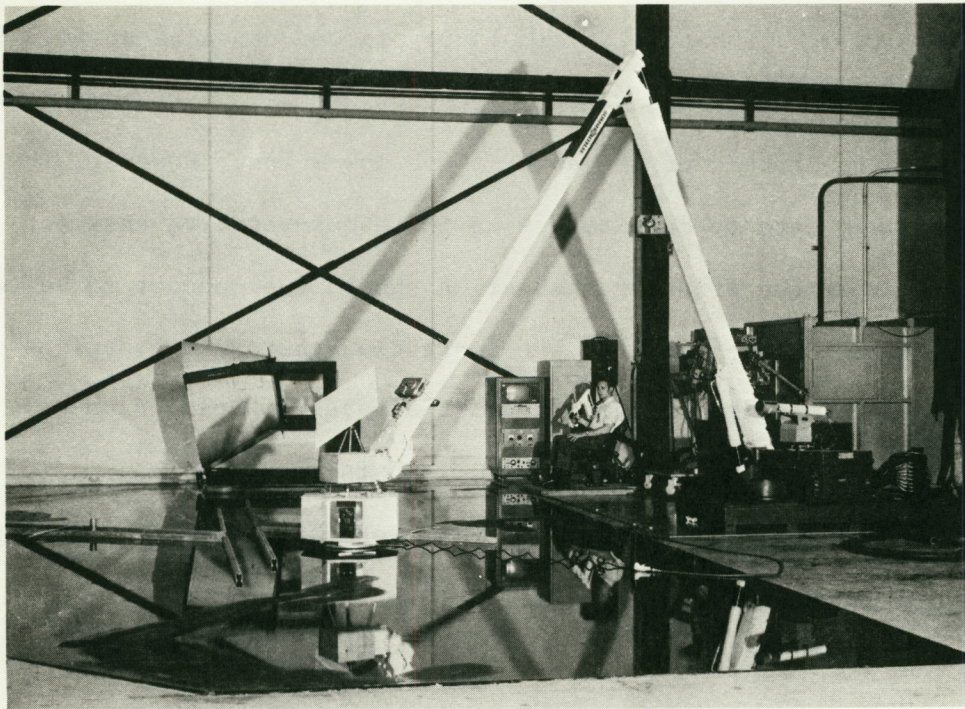
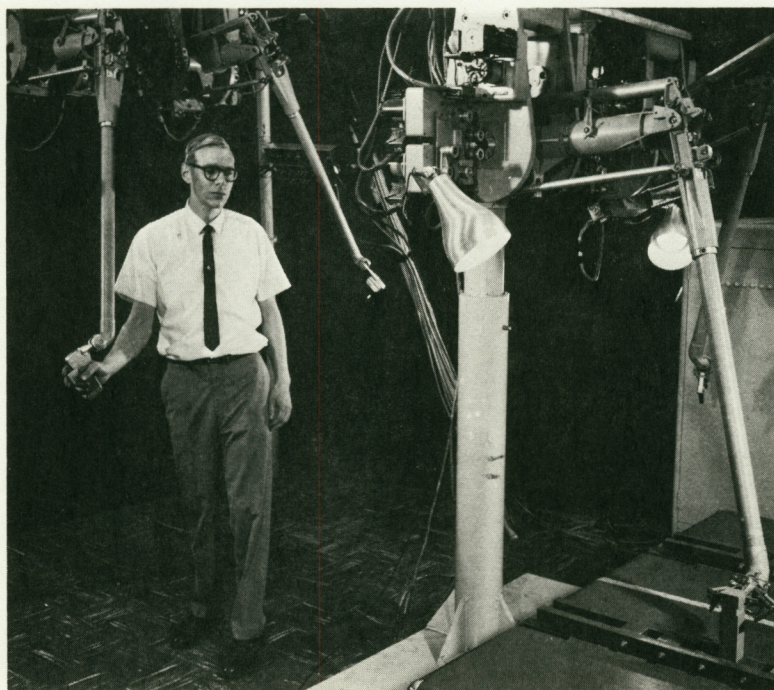Figure 2-1. Space Manipulator Experimental Setup in Bld. 13 NASA/MSC.

Figure 2-2. Model E-2 Master Slave Manipulator Arm Shown in Previous Task.

SECTION 3

CONCLUSIONS AND RECOMMENDATIONS

The effect of large changes in compliance seems to effect the task performance only slightly and, therefore, the more compliant space designs should not have a significant decrease in task performance capabilities. However, the results here are only valid if the manipulator/booms response is over damped. A very limber but under damped system would be another story. The degraded performance of the CAM 1400 without force feedback verify this conclusion. Here the system is not as highly damped and it is evident from the operator's performance that the tasks became much harder. The CAM 1400 without force feedback appears to have less damping because "step" inputs can be easily put in by the operator and with the desire to retain responsiveness in the boom, overshoots result. With force feedback, the operator cannot put in step inputs since the master immediately resists the operator's inputs. Thus, it is recommended that future "limber" space manned control designs include a force feedback replica master plus as much structural damping as practical in the boom segments.

There are many avenues of investigation yet to be explored using the CAM 1400 facility. However, just two are mentioned here. First, to look into the question of damping, it is proposed that a tracking test be set up using the CAM 1400 but which will give the operator the appearance of an under damped system. This can be accomplished by mounting a small TV camera on a slightly curved track attached to the end of the CAM 1400. The operator would view the TV picture as he attempts to track an object. Smooth inputs will not set the TV camera in motion, whereas step inputs would. Video tape and/or time on target could be used to analyze the results. The second area of investigation would be to extend the capture tests to gather more data and also to use more degrees of freedom. Modification of the CAM 1400 hand controller would allow 6 degrees of freedom simulation which would allow setting up of proper satellite capture velocity limits for future space designs.

SECTION 4

EXPERIMENT I: PENDULUM CATCHING

4.1 Objective:

To determine the effect of manipulator compliance in a work paced task

wherein manipulator force is used to absorb the energy of a moving mass. Com-

pliance as used here is the amount of master slave desynchronization for a

given slave force (inches/pound).

4.2 Description of Apparatus and Procedure:

A heavy long pendulum was set in motion so that it intruded into the E-2

manipulator slave working volume as shown in Figure 2-1. The manipulator grabbed

the pendulum near the maximum displacement point and thereafter applied forces

retarding the motion with the goal in the subject's mind of stopping the pendulum's

motion as quickly as possible.

The pendulum was about 33 feet long and had a mass of 400 lbs. The amplitude

of motion was $\pm$ 24 inches. A pointer extended downward from the mass to the floor,

and with the help of markings on the floor, the subject could see visually the

line of travel and a $\pm$ 1 inch dead zone used as the rest position. The dead zone

allowed the subject and experimenter not to have to be concerned with making judg-

ment as to whether the mass was fully stopped.

The independent variable tested was the manipulator's compliance. While in

all cases of compliance, slave forces were fed back to the master, varying amounts

of master-slave desynchronization were needed, thus changing the eye-hand-force

vector relationships. The dependent variables were the time it took to bring the

motion to rest, the displacement pattern of the pendulum, and the force pattern of

the manipulator. Several steps were taken to minimize the learning curve effects.

First, the motion was limited to one plane, that being the vertical median plane of

the manipulator. Thus, only elbow and smaller amounts of shoulder motion were

needed. Secondly, a rectangularly shaped piece about 1-1/2" x 1-1/2" x 3" with a hole drilled down the long axis acted as the grab point for the manipulator. This minimized wrist twisting moments and allowed purer force inputs without wrist distortion forces and permitted more alignment error of end effector with block. To further ensure good alignment and minimize grabbing errors, the procedure called for the subject to watch 1-1/2 full swings before grabbing the mass. During the first peak the subject aligned the manipulator jaw up only a couple of inches back from the grab point. Additionally, the subject was seated immediately next to the plane of motion just back of the furthest pendulum swing point. Therefore, vision was excellent, thus minimizing one of the biggest sources of uncertainty in manipulator operations.

To measure the displacement, a potentiometer-pulley-cable arrangement was used to record pendulum position and voltage sensing circuits were used to measure the torque in the appropriate E-2 motors. The three motor signals, (i.e., shoulder, elbow and upper arm roll or Z, X, & Y) measured the control winding voltage drop (2 ϕ AC servo motors are used on E-2) thru a RMS voltage meter. The voltmeter output, the pendulum position signal and a task start and stop reference signal were recorded on a strip chart recorder.

The subjects were given only a small amount of practice prior to the actual recorded runs. This consisted of the subject grabbing the pendulum at the rest position and moving it away from equilibrium. This acquainted the subjects with the feel for the compliance setting.

Several hundred feet of 16 mm. movie film was shot of the test set-up, typical runs at low compliance (with and without force feedback), the instrumentation, and the E-2 and its motions. This film can be obtained from MSC/NASA contact, Mr. R. B. Davidson.

4.3 Subjects

Nine subjects were used, all being engineers associated with NASA. The range of experience ranged from one subject quite familiar with the E-2, to the majority who had never operated the E-2 prior to the test day.

The following instructions were given:

(Read first time only)

The objective of this experiment is to determine the effect of manipulator compliance in a task where the manipulator is used to absorb the energy of a moving mass. Compliance as used here means the amount of master motion to produce a given slave force and is measured in inches per pound.

(Read every time)

The trial will begin by the releasing of the pendulum away from you. Allow the pendulum to swing toward you one time, using this swing to align the manipulator jaw with the white grabbing block. On the second swing, grab the weight at the near end of its travel and try to bring the pendulum to rest at its mid rest position marked on the floor, as quickly as possible.

(Read after first trial)

The compliance of the manipulator is different than your last one but the force you can exert is the same.

Any questions?

Each subject was given ten to twelve runs in succession at each of the first three compliance settings but only five runs on the last setting which was used as a check since the experimenters felt the learning was well established. Each run took less than 30 seconds so the total time would preclude any fatigue factors. Most subjects ran the first test on the first afternoon and the three succeeding tests the following day.

4.4 Results:

It was expected that with higher compliance the task times would increase, and indeed this turned out to be so. The data from each compliance setting for

each subject was plotted as trial number versus task time. This, of course, showed learning curve trends as well as distribution of data. A sample of four such learning curves for the low compliance test (the first data taken) is shown in Figure 4.2. It is evident that for three of the four subjects, the last five trials show much more consistency than the first five and that the learning curve is almost flat. For subject RBD, three of his last five times fall within the other subjects times. Thus, to analyze the data the last five trials are used but also points above a certain task time are discarded. The rejection time turned out to be slightly greater than the mean of the accepted data plus two standard deviations. Table 4-1 shows the number of points discarded for each subject for each of the four compliance settings. The rationale for discarding these points is that some other reason than the particular compliance setting most likely is the cause of the high reading, such as slippage of the grip on the mass or the subject "experimenting" to find a quicker way. On the other hand, the number of discarded points increases steadily with higher compliance in the first three tests even though experience is increasing but reduces when experience comes into play stronger on the last runs where compliance was decreased.

The means of the accepted task time at each compliance value is plotted in Figure 4-3. The compliance of the elbow is used since it is the primary motion involved. Compliance of each point at each setting is given in Table 4-2. Figure 4-3 also shows the $\pm$ one standard deviation values of the data. By using the student "t" test between adjacent compliance settings, it can be shown that all the means come from different population means to the 90% confidence level, except the second and third compliance settings which are at the 85% level.

If one refers to Table 4-1, it can be seen that a group of four subjects (EGB, RLB, LEL, & GR) had only three rejected times between them. Their means are also shown by the small arrows in Figure 4-3. Only slight differences

appear in the mean and also in the standard deviation wherein one might suspect the data should be less variable.

The final presentation of the data in Figure 4-4 plots the increase in task time over the theoretical minimum task time if the manipulator forces were applied correctly and at the proper times. This theoretical minimum assumes the operator applies the maximum available force in the proper direction and switches sense when the velocity of the mass changes. The time is approximately 4.50 seconds based on an assumed maximum E-2 force of 7.5 lbs. Actually, some of the times were less than the theoretical, but perhaps this is because of measurement errors and most likely, due to impacting the mass when grabbing it. This increase in time more dramatically shows the degradation due to increase in compliance.

In Figure 4-5 thru 4-8 are shown four typical traces of the pendulum displacement, and E-2's elbow, shoulder, and upper arm roll motor voltage versus time. Figure 4-5 shows subject RLB's second low compliance run and is typical of most of the inexperienced subject's response. That is, the elbow torque is not applied in a near step-wise response. By his eighth trial at this compliance, shown in Figure 4-6, the response is much smoother and step-wise although there is a dip in the elbow response, probably due to the fingers slipping slightly. Also, the shoulder motor voltage in Figure 4-6 is much more in proper synchronization than in Figure 4-5. Most of the faster setting time trials look like Figure 4-7 which is the same subject but at the highest compliance setting. Thus, the curves look similar irregardless of compliance setting, except for the slope of the elbow response which is about twice as steep in the low compliance mode as that in the highest compliance.

Finally, Figure 4-8 shows the same traces for subject EGB's fourth trial without force feedback in the low compliance mode. Obviously, shoulder and upper arm roll forces are greater than they should be and the elbow forces are not applied in the correct manner either as compared to Figure 4-7. The traces of

this run can be co-ordinated with the movie documenting the test set-up. This run corresponds to EGB's second run shot without force feedback.

4.5 Conclusions:

The fact that performance in this task is degraded by increase in compliance is not surprising at all. Master/slave manipulators have always had as one of their main design criterion, the stiffness of the system and, therefore, stiff structures and as high as possible servo bandwidths have been used. However, some manipulator designs for space applications may not have the desired low compliance. The data presented here can lead one to conclusions as to how performance in an energy absorption task can be affected by increase in compliance.

Looking at Figure 4-4, one concludes that with low compliance, the operator can achieve almost optimal performance and that increases in compliance increase manifold the increment over optimum time. It is interesting to note that small changes of compliance at low compliance values have much more affect than the same percentage change at high compliance values. Thus, in future space tasks (those which would correlate with the type of task described herein) where precise control and energy absorption are desired, increase in compliance will add appreciably to the increment over the theoretical minimum.

On the other hand, one may view the results from an energy absorption per unit time basis, or in other words, compare total task time. One could then, from Figure 4-3, draw such conclusions as an increase of compliance by a factor of almost 13 will only increase the energy absorption per unit time factor by 18%. While this may be a more realistic way to assess the impact of increases in compliance, whichever way one interprets the results, one must remember the restrictions of the test. The main restriction is that compliance was increased by increasing servo compliance and not structural compliance. Although the operator could not probably discern the difference in feel or how the task looked,

there is an important difference between the two compliance factors, that being the amount of damping. With structural compliance, high damping rates are difficult, whereas with the servo compliance, especially bilateral controls, effective damping is inherent. In fact, a test was run on the E-2 to test the damping, wherein the master was locked and the slave released from a step input. There was essentially only one overshoot or a damping factor of about $\widehat{\mathfrak{F}} = 0.4$.

With less damping, a more compliant system will have less control ability and would, for example, further increase the time in this experimental task. However, the net effect can only be determined for the manipulator design and task in question.

It is apparent that in this task, the operator could not learn to compensate for the additional compliance. There was just that much more master motion required to obtain full force at the slave and this took time.

Finally, it should be noted that several runs were made without force feedback in the master. It was apparent that the task times were higher, although not enough times were taken to statistically show this. A more surprising result was the loss of control the manipulator had on the pendulum in that when bringing it to rest, i.e., the deviation from the original plane of motion was greater. Also, it was difficult to sense when the pendulum was near the rest point and larger motions resulted as the E-2 released its grip on the mass. The difficulties can be imagined perhaps by comparison of Figures 4-7 and 4-8, the latter showing the large forces applied by the slave unknown to the operator.

COMPLIANCE SETTING

Subject	Low	Med High	High	Med Low	Total
EGB	1	0	0	0	1
RLB	0	0	0	0	0
RAC	3	2	5	1	11
MCD	0	3	2	1	6
RBD	2	0	2	1	5
DAK	0	2	1	2	5
AJL	0	2	5	3	10
LEL	2	0	0	0	2
GR	0	-	0	0	0
Total Rejected	8	9	15	8	
Total Accepted	37	31	30	35	

TABLE 4-1. Number of Data Rejected $(> \bar{X} + 2S_x)$

Compliance	Test Order	Joint/Motion		
		Elbow "X"	U. Arm Roll "Y"	Shoulder "Z"
Lowest	1	.144	.206	.047
Medium Low	4	.4	.4	.2
Medium High	2	.8	.8	.4
High	3	1.85	1.6	.65

TABLE 4-2. Measured E-2 Compliance Valves @ 5 lb. Force Level
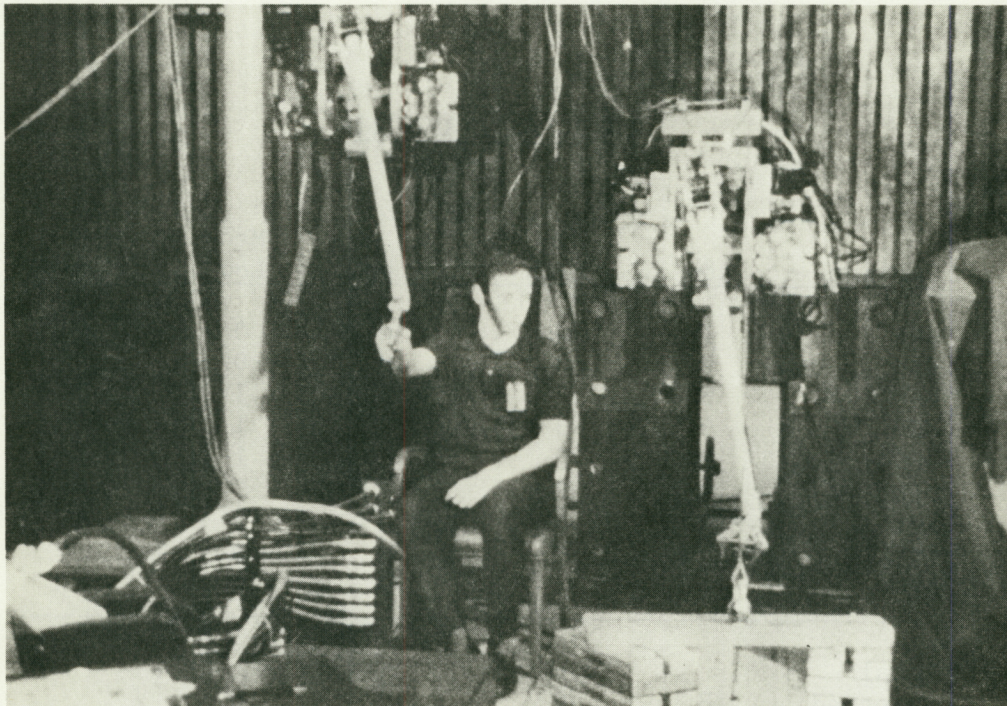
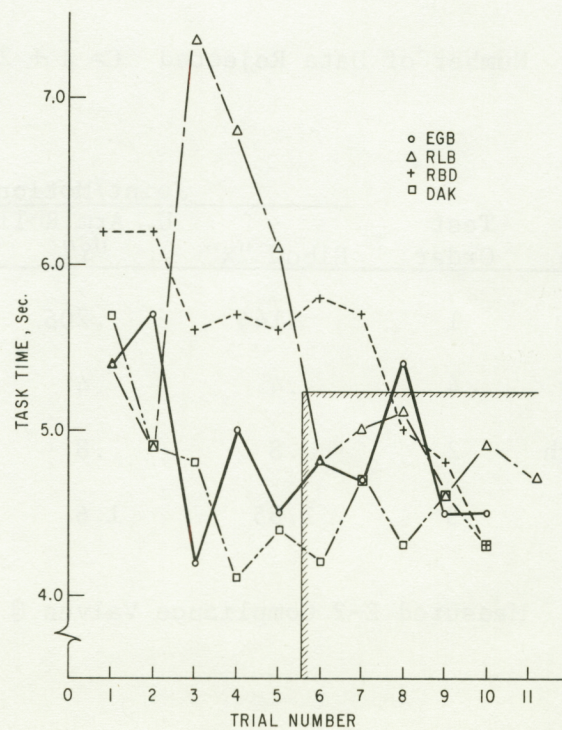Figure 4-1.   E-2 Pendulum Test Setup.

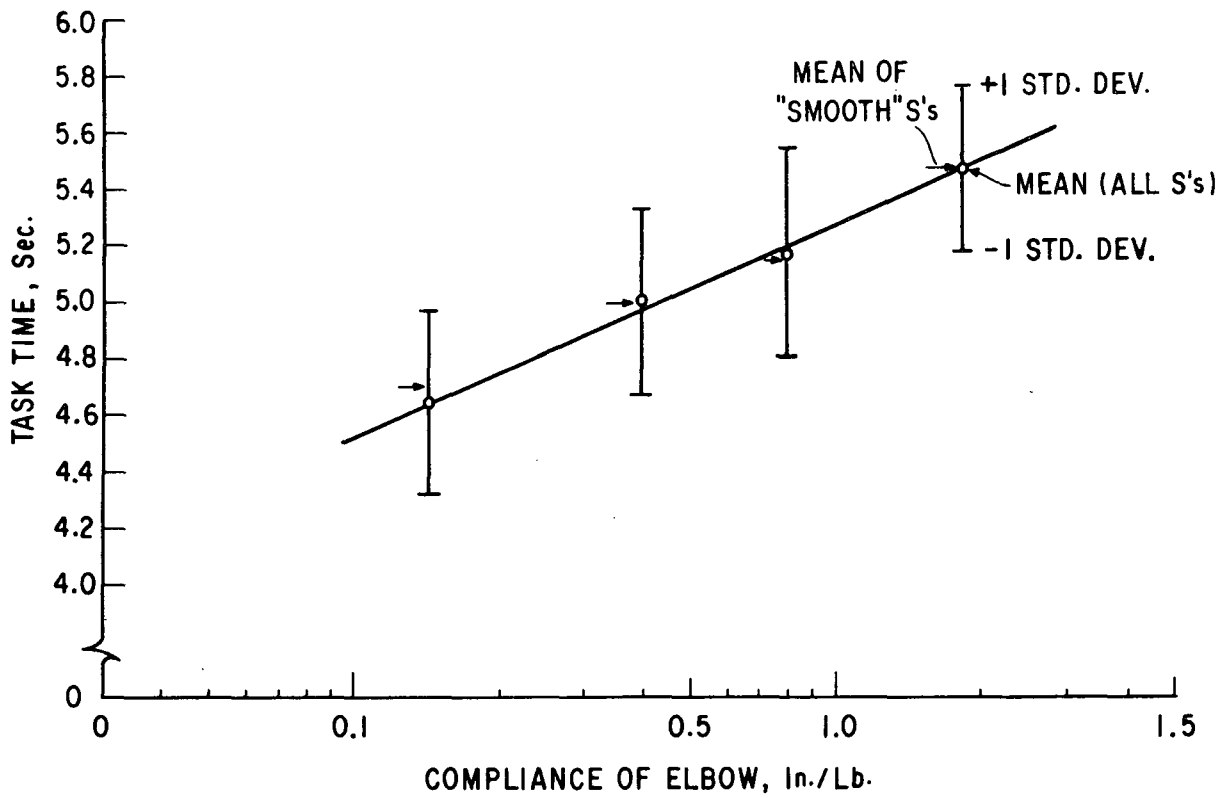Figure 4-2.   Learning Curve for Four Subjects.
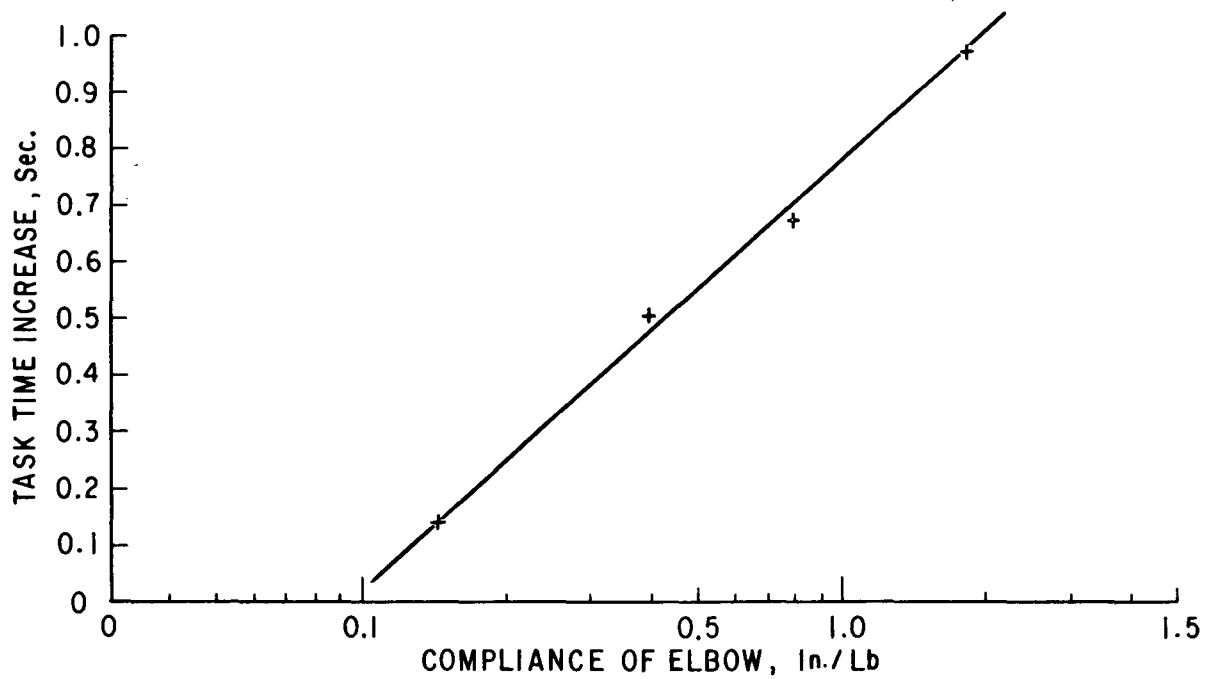
Figure 4-3.   Total Task Time vs Compliance.

Figure 4-4.   Increase in Task Time Over Theoretical Minimum
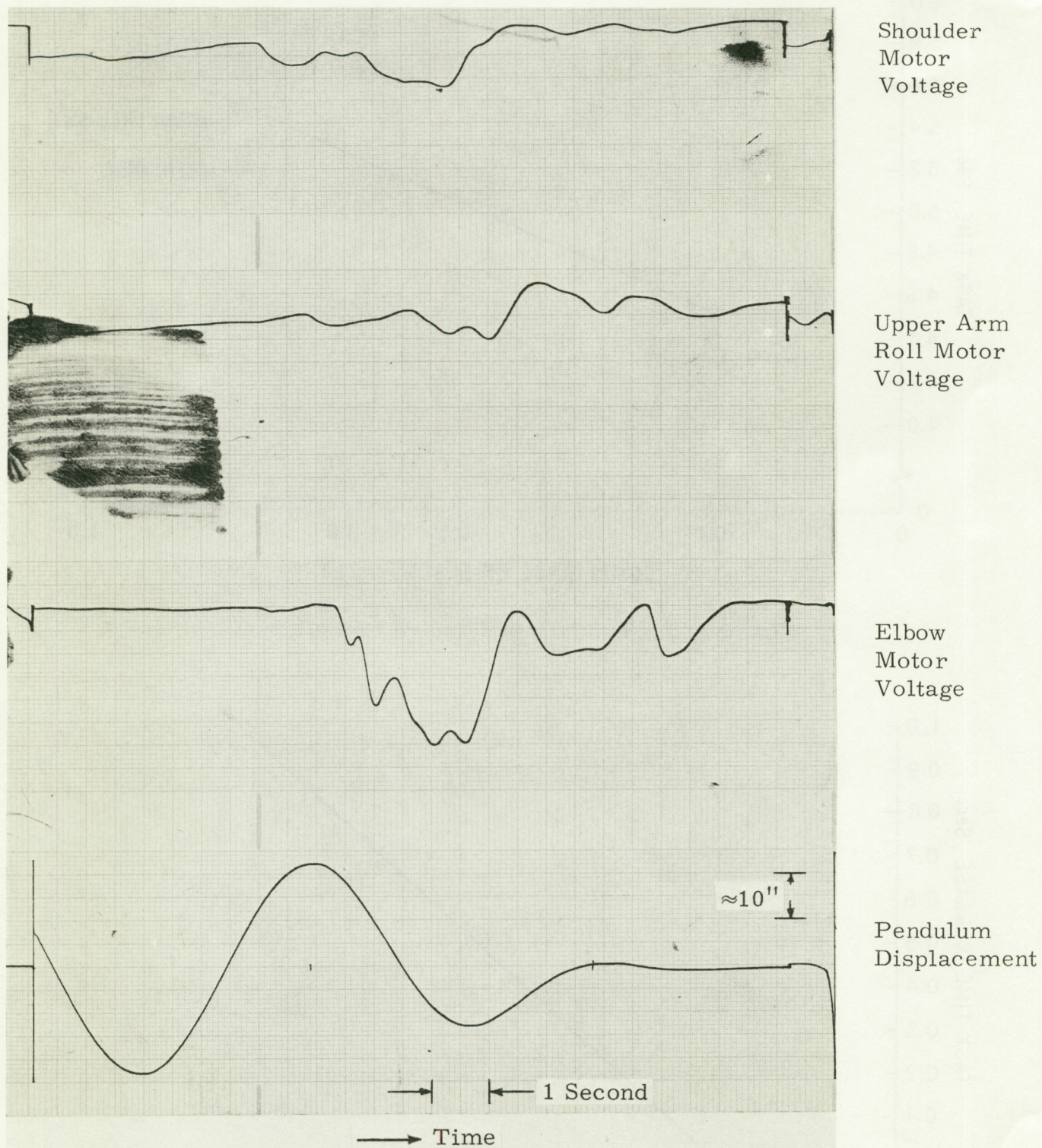as Compliance Increases.

Figure 4-5.   RLB's 2nd Run at Low Compliance.

Shoulder
Motor
Voltage

Upper Arm
Roll Motor
Voltage

Elbow
Motor
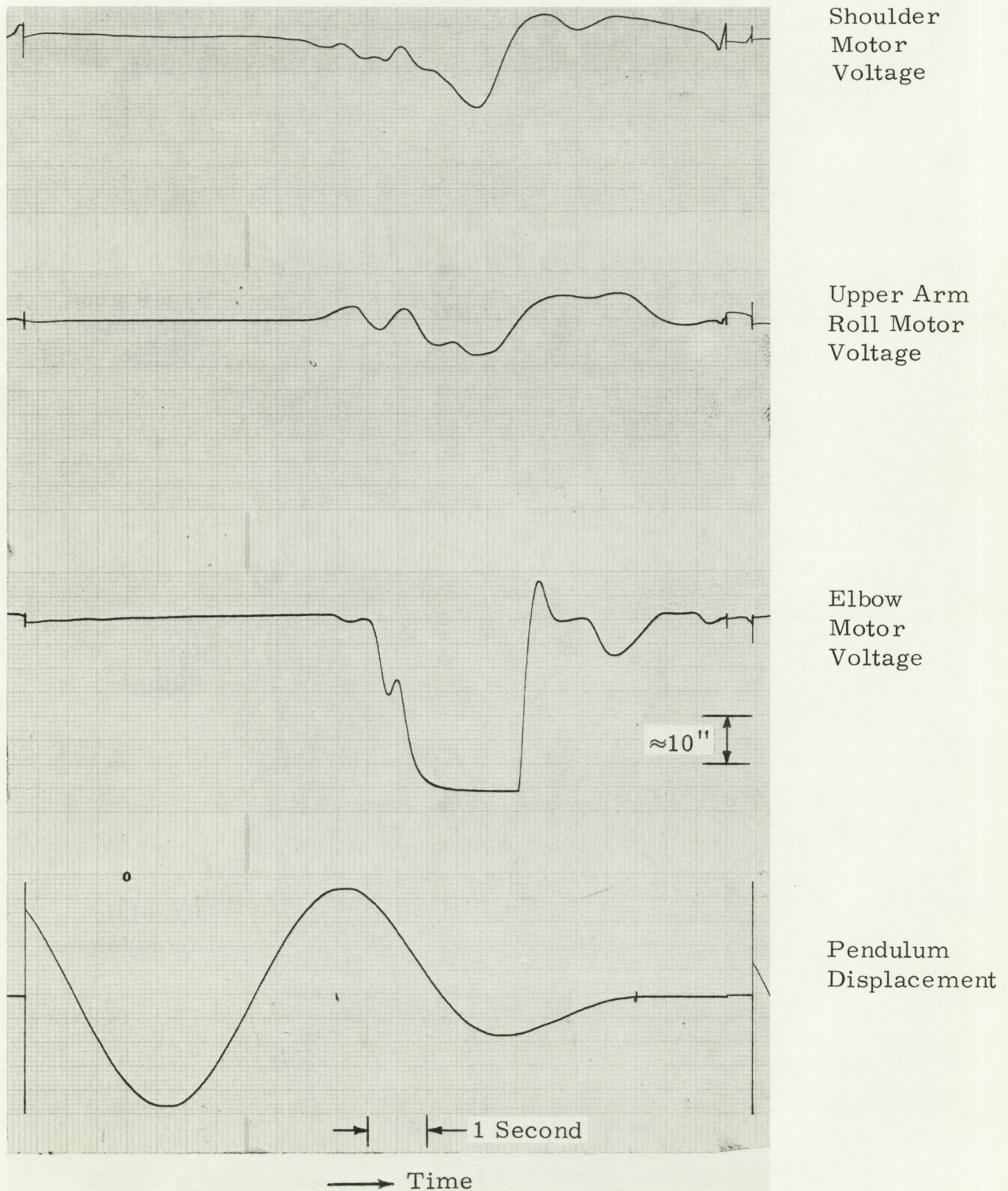Voltage

≈10"

Pendulum
Displacement

1 Second

Time

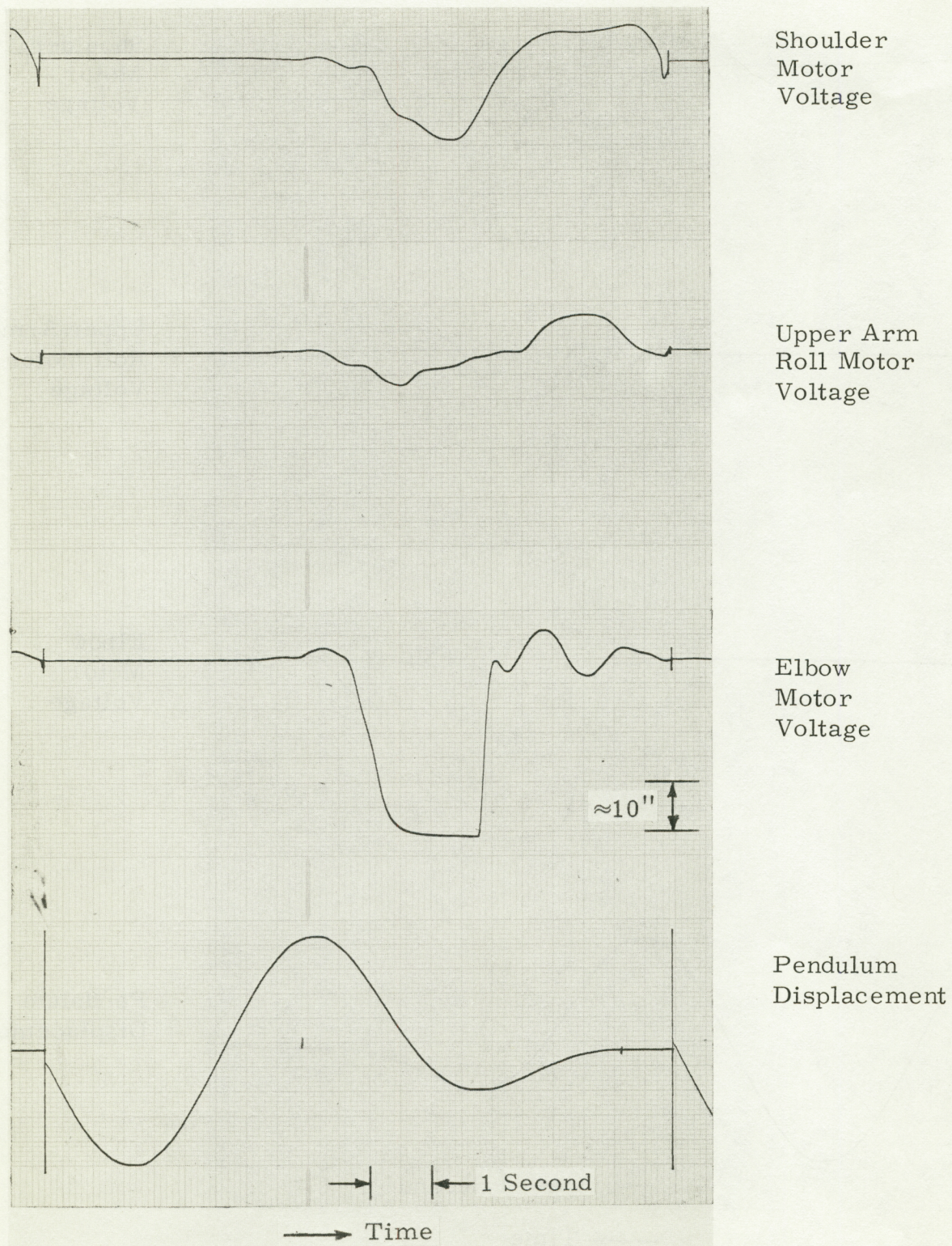Figure 4-6.   RLB's 8th Run at Low Compliance.

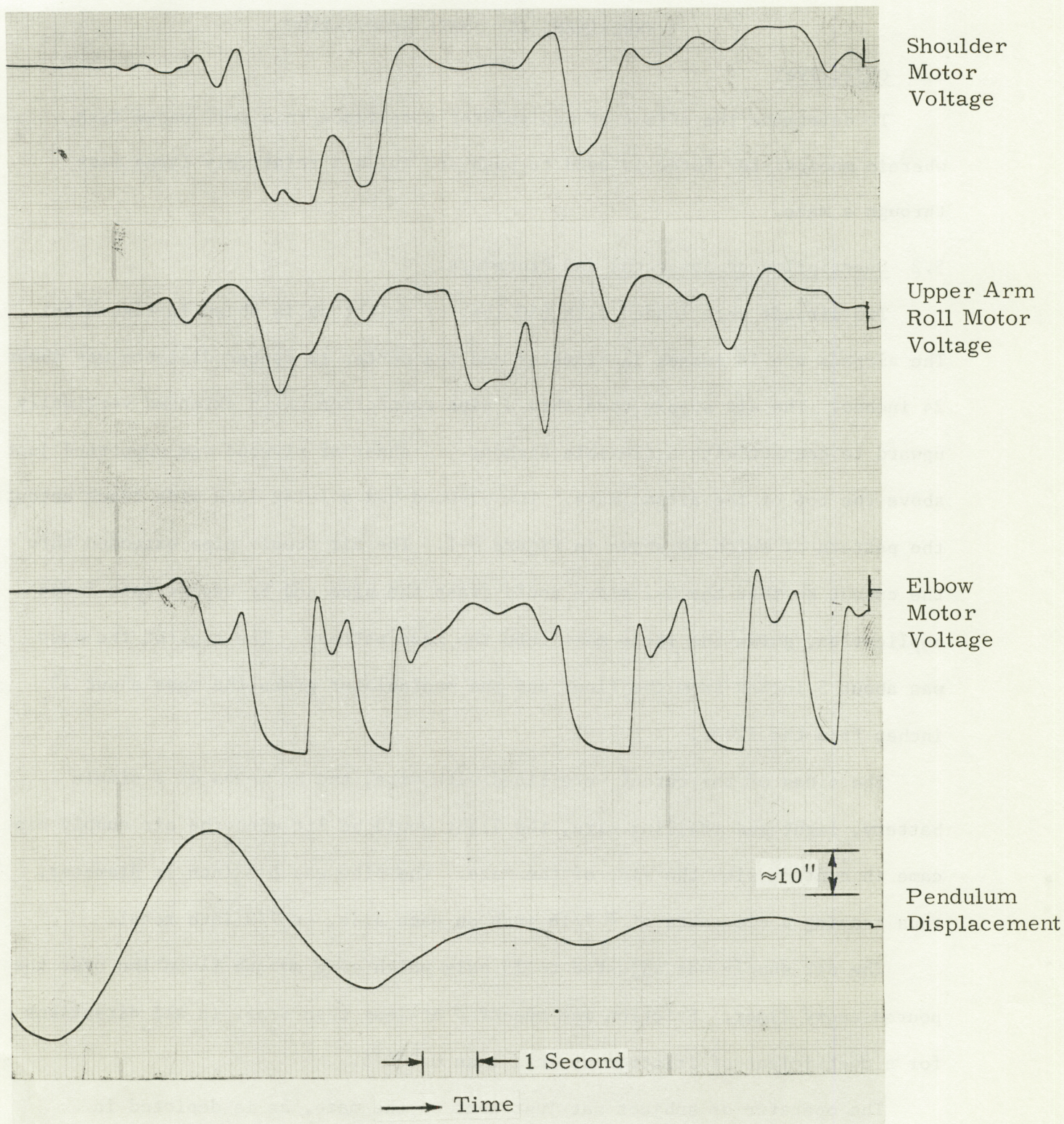Figure 4-7. RLB's 9th Run at High Compliance.

Figure 4-8. RLB's 4th Run with Low Compliance and No Force Feedback.

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SECTION 5

EXPERIMENT II: MAZE NEGOTIATION

5.1 Objective:

To determine the effect of manipulator compliance in a self paced task

wherein manipulator force is used to push and guide a relatively large mass

through a maze.

5.2 Description of Apparatus and Procedure:

Two airpads were loaded with 650 lbs. of weight as is shown in Figure 5-1.

The airpads are 18 inches in diameter and the center to center distance was about

24 inches. The air supply came thru a pipe connection which extended vertically

upward to connect with a flexible airhose. A sheet of plywood was supported just

above the top of the airpad mass. The plywood had a 1-1/2 inch wide track cutout,

the pattern of which is shown in Figure 5-1. The air supply pipe extended thru

the cutout so that the E-2 slave could grasp the pipe and by appropriate force

application, guide the large mass thru the maze pattern. The c.g. of the mass

was about 5 inches from the floor and the manipulator grasp the mass about 18

inches from the floor.

The sides of the cutout were lined with wire, and by means of a simple

battery, light and trailing wire, the light would be lit when the air supply pipe

came in contact with the side of the maze. The pipe was 5/8 inch in diameter,

thus leaving a clearance of $\pm$ 7/16 inch on each side, or 7/8 inch total.

The air supply was adjusted to 15 psig which gave smooth flotation over the

poured epoxy floor. Friction was measured at less than 8 oz. in all directions

for a coefficient of friction of less than 0.00075.

The operator or subject sat just next to the maze, as is depicted in

Figure 5-1. The eye to corner distance was about 55 inches as shown. Thus, good

vision, acuity and depth perception were assured. The operator used his right

hand to control the master, looking to his left to see the slave. Thus, although master and slave were aligned, eye-hand co-ordination could have been a bother to some subjects.

The independent variable tested was the compliance of the E-2 manipulator. This was varied, as in the pendulum test, by varying the servo gain. The dependent variable was the task time to complete the maze. The subject was timed in one direction, allowed a short rest, and then timed in the opposite direction. The number of errors was recorded as well as their location, although often times the run would be restarted after the first error.

Eight of the nine subjects who performed the E-2 pendulum test were used, thus all were engineers acquainted with the space manipulator project. Two of the subjects did not complete the full set of tests. Initially, four compliance settings were used with 6 runs at each setting. It was found after the initial data, that apparently a great deal of learning was taking place, as well as difficulty in getting all the subjects to try equally as hard. The initial instructions asked the subjects to consider mass and maze to be "space" hardware which was to be maneuvered as rapidly as possible but that contact was to be avoided. Thus, there were differences as to approach, i.e., some were more cautious than others. After this first set of about 24 runs each, the subjects were told not to worry too much about making contact, i.e., that contact was to be avoided, but that a fast time was more important. The subjects then ran 10 to 20 runs at each of three compliance settings as is listed in Table 5-1.

DATE OF TEST

SUBJECT	3/23	3/24	3/29	3/31	4/3	No. of Practice Runs
EGB	D-11	-	C-20	B-17	-	33
RLB	D-16	C-9	-	-	B-24	27
MCD	D-18	C-14	-	B-27	-	24
RBD	D-14	-	C-16	B-22	-	27
LEL	D-12	C-9	-	B-21	-	29
AJL	D-11	-	-	-	B-14 & C-15	27

LEGEND   B - High Compliance (8" deflection for 5 lbs.)

C - Low Compliance (1" deflection for 5 lbs.)

D - Medium High Compliance (4" deflection for 5 lbs.)

B-11 means 11 runs were made at B compliance setting

TABLE 5-1.   Number of Runs for E-2 Maze Test in Chronological Order

5.3 Results:

The data is presented graphically in learning curve in Figure 5-2 thru Figure 5-7. The task time is plotted as a function of trial number. Also recorded is the number of errors (touches) made during the run and an asterisk is used to indicate that the run was restarted (two asterisks if restarted twice, etc.).

Superimposed on the data is the computer generated best fit (from a least-squares criterion) linear curve and a 2nd order curve. Table 5-2 gives the coefficients of these curves. In all but one case, the linear learning curve shows a learning effect. Subject EGB's "C" compliance tests shows a slight positive slope, i.e., no learning took place. It is apparent from study of the learning curve data that in both of the first two compliance settings, not enough data was taken so that the flat portion of the curve was reached. This is shown by comparison of the average linear curve for each compliance setting summarized in Table 5-3.

Compliance Setting	Linear Learning Curve
"D" – Medium High	$T = 19.75 - .247\ N$
"C" – Low	$T = 17.46 - .249\ N$
"C" – Low (w/o EGB data)	$T = 18.31 - .369\ N$
"B" – High	$T = 17.79 - .171\ N$

T – Task time, N – Trial number

TABLE 5-3. Average Learning Curve for 5 Subjects.

Since subject EGB had 27 errors in his "C" compliance setting, an average is shown of the other 4 subjects. This average is beat when making comparisons since the average error per trial figure would compare with the other data.

Figures 5-8 and 5-9 present the individual mean task time (time without errors only) for the 6 subjects as a function of compliance and in chronological order. The curve in Figure 5-8 shows virtually increasing time as compliance increases as one would expect, but then the curves dip down at the highest compliance setting. This is cleared up by looking at Figure 5-9 where the effect of learning is evident.

5.4 Conclusions:

The effect of compliance is definitely discernable, although clouded by the fact that not enough data was taken for the first two settings of compliance. A brief look at the data does not allow valid conclusions, relative to compliance, to be drawn since the data is overshadowed by the learning taking place. The conclusion one might draw from Figure 5-8, that compliance had no effect and that learning was going on continually irregardless of compliance setting, is not correct. If one looks at the data individually, i.e., Figure 5-2 thru 5-7, one notes that in most cases not enough data was taken to determine the flat portion of the curve, whereas in the high (last) compliance setting test, the bottom of the curve is apparent. This is seen by looking at the minimum point of the 2nd order curves, all of which "bottom out" for the last setting but rarely do so in the first two settings. The average linear learning curves as summarized in Table 5-3, shows the slope to be higher in the initial two cases than the third and thus after 10 trials the composite predicted times would be:

Low Compliance   T = 14.62 sec.

Mid-High Compliance   T = 17.26 sec.

High Compliance   T = 16.08 sec.

Although mid-high compliance has the highest predicted time, remember it was the first data taken, whereas high compliance was the last data. Thus, learning is still in this summary but the fact that the earlier data (low

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compliance) has a lower predicted time indicates an increase in task times when increasing compliance. Comparison of the data in this manner, as well as careful study of the individual curves, show then that higher compliance adversely affects task performance. However, it is to be also concluded that the effect was not a very great one from an overall task time point of view. A theoretical task time can be calculated assuming; 1) constant maximum force inputs in the proper direction, 2) proper and immediate shifting of the force vector, and 3) the 8 oz. friction level will not be significant (it slows acceleration, but speeds deacceleration and thus tends to cancel out). If one assumes a 6 lbs. force capability, the minimum theoretical time is 12.5 seconds. Thus, the times are very near optimum on some runs which is remarkable in itself.
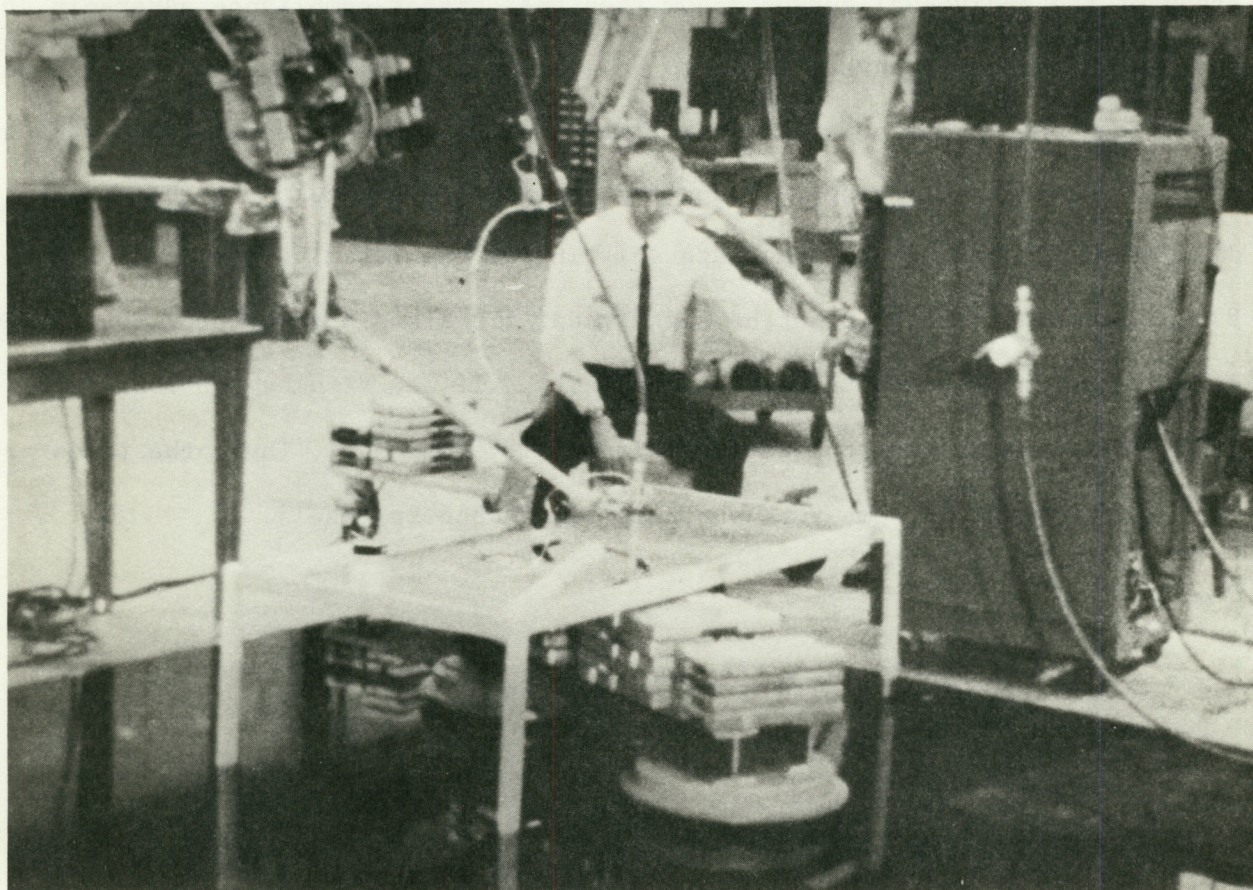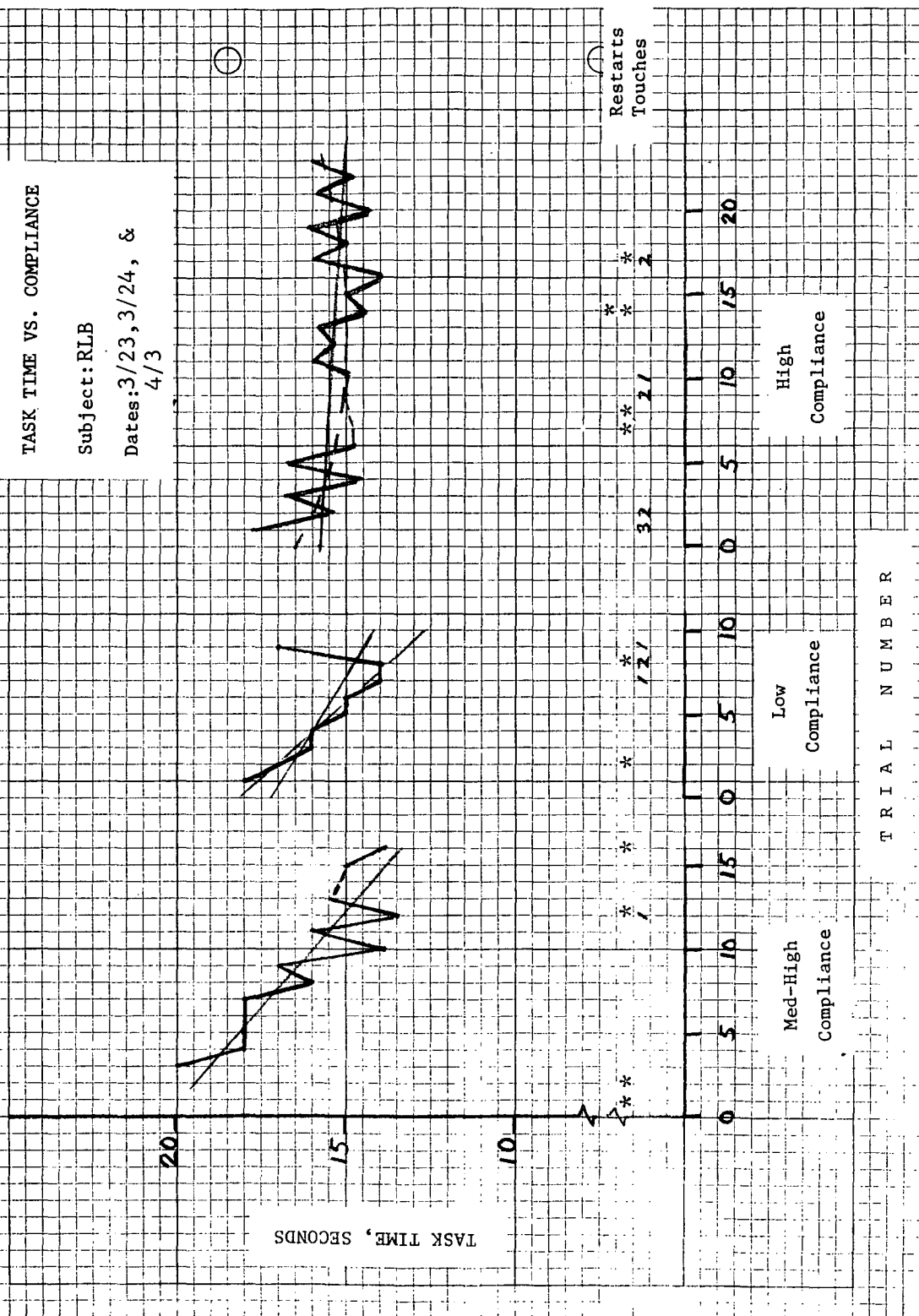
Figure 5-1. The E-2 Maze Test Setup.

Figure 5-2
E-2 MAZE TESTS

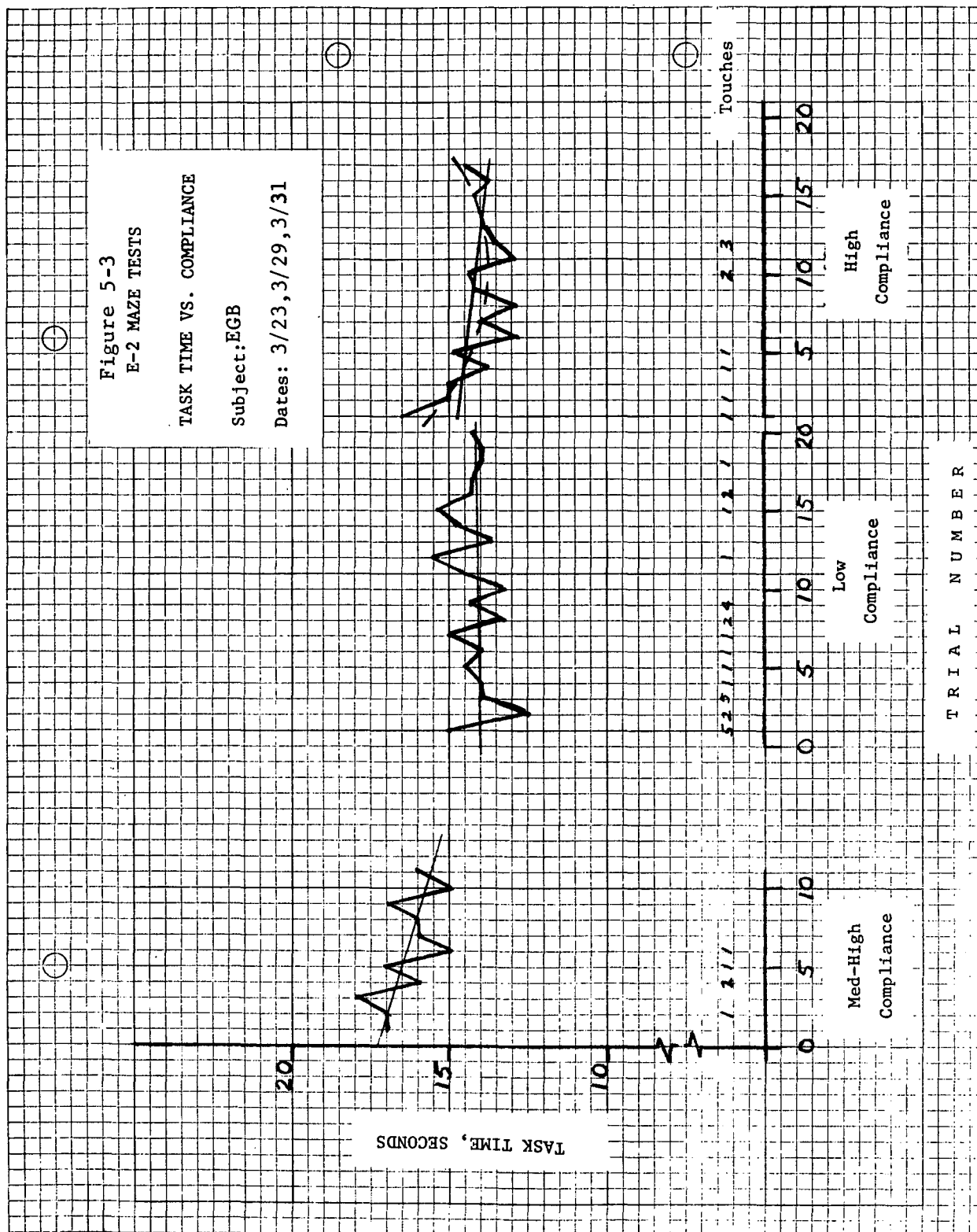TASK TIME VS. COMPLIANCE

Subject:RLB

Dates:3/23,3/24, &
4/3

Restarts
Touches

TASK TIME, SECONDS

20

15

10

Med-High
Compliance

Low
Compliance

High
Compliance

TRIAL NUMBER

Figure 5-3
E-2 MAZE TESTS
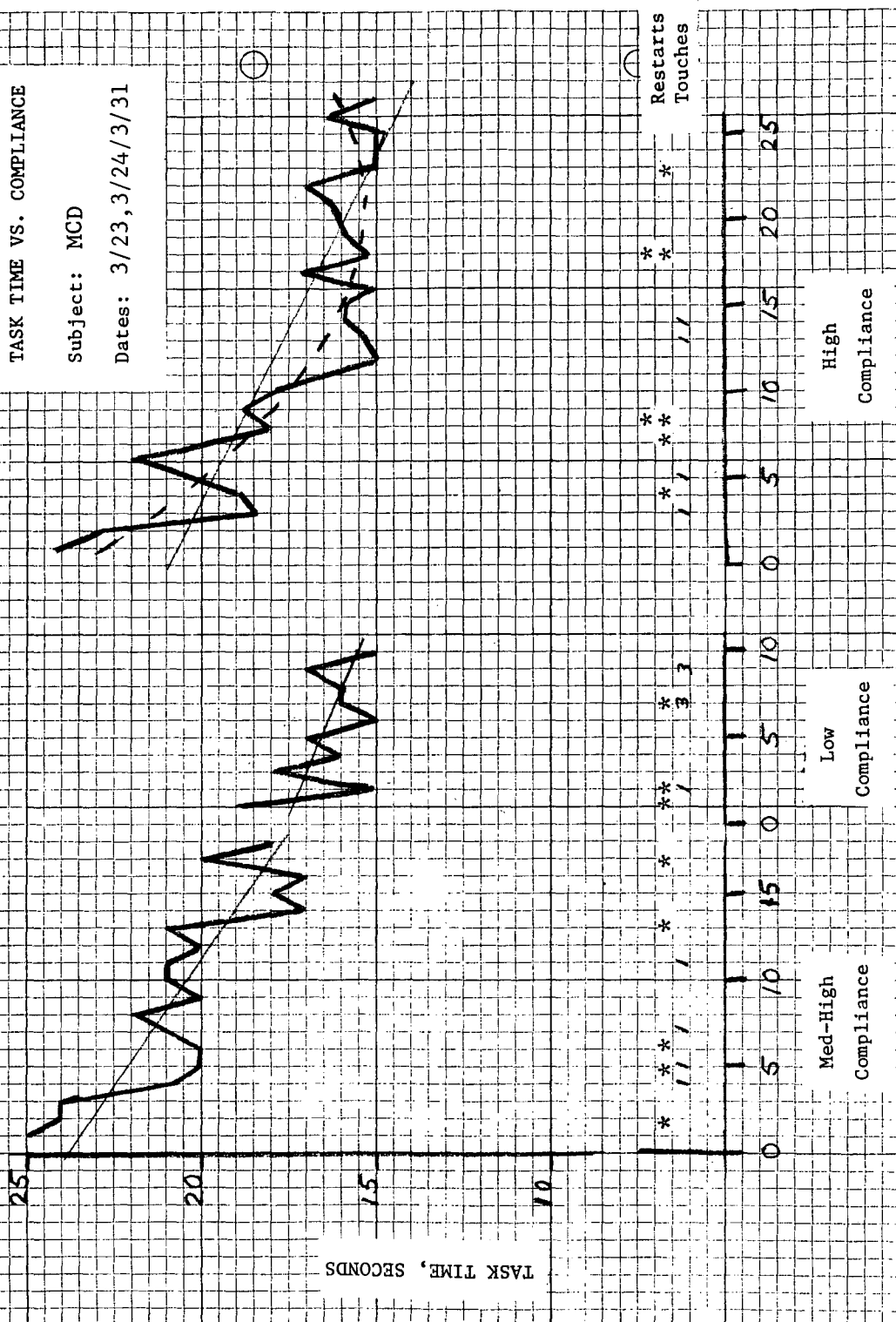
TASK TIME VS. COMPLIANCE

Subject: EGB

Dates: 3/23, 3/29, 3/31

Figure 5-4
E-2 MAZE TESTS

TASK TIME VS. COMPLIANCE

Subject: MCD

Dates: 3/23,3/24/3/31

Figure 5-5
E-2 MAZE TESTS

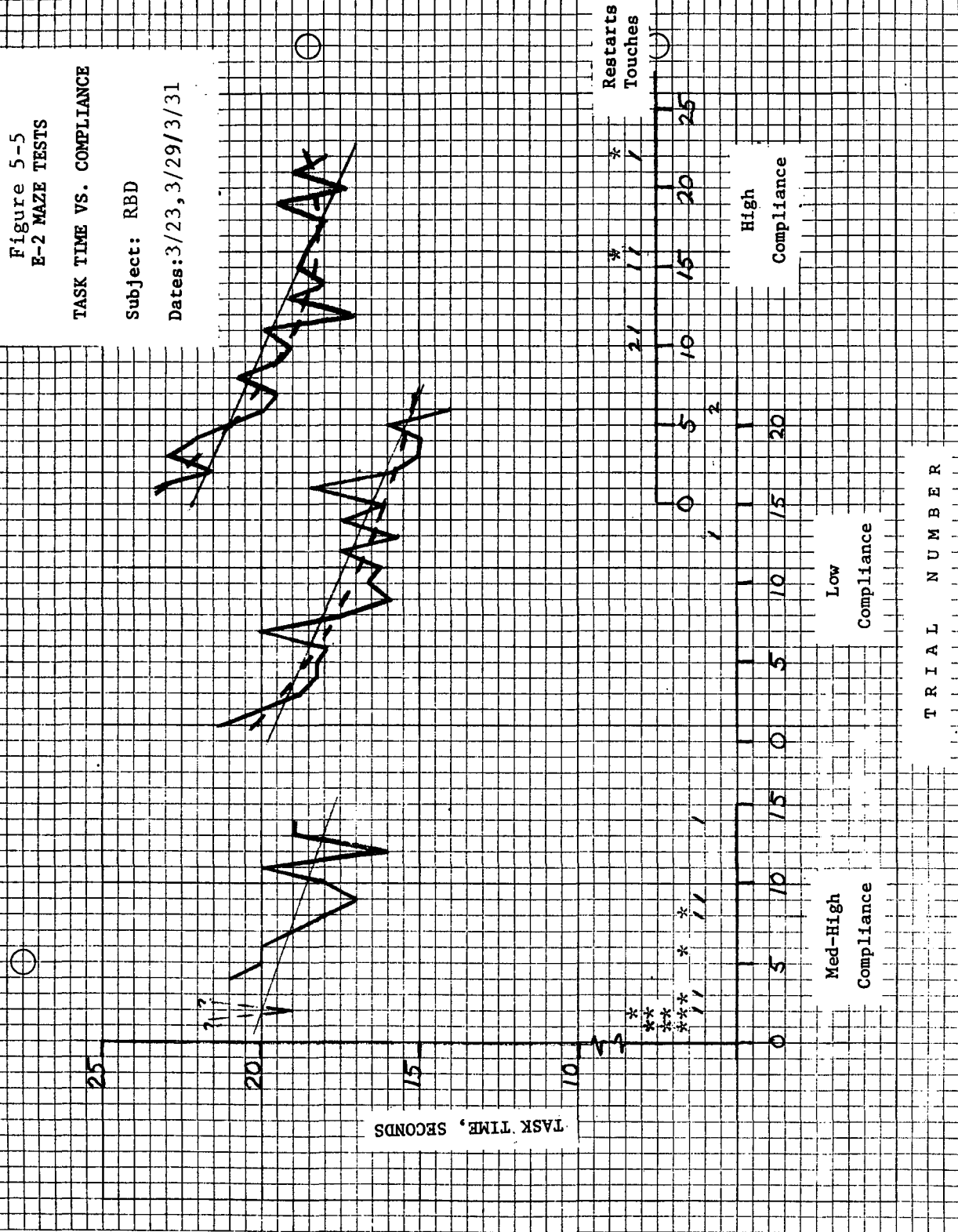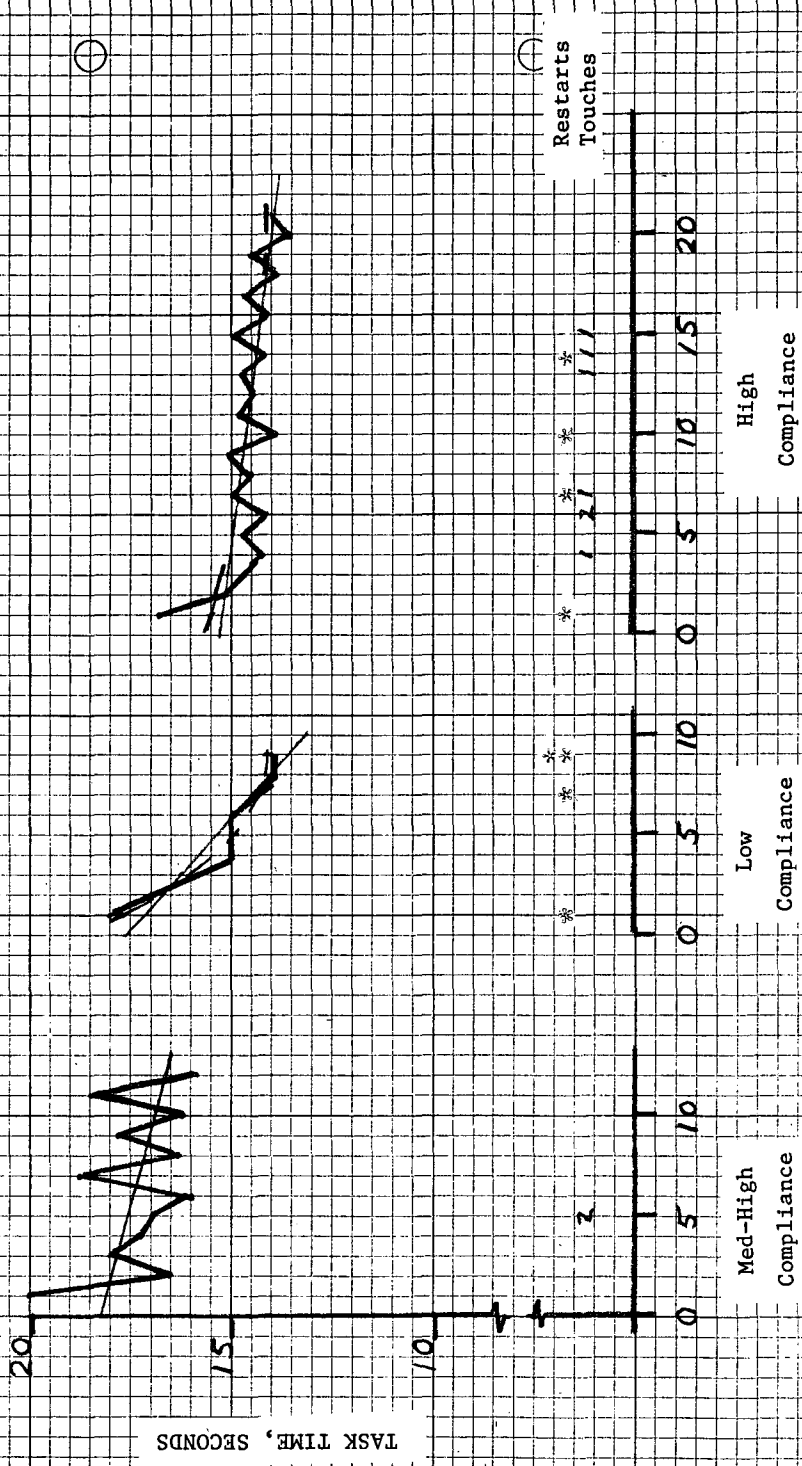TASK TIME VS. COMPLIANCE

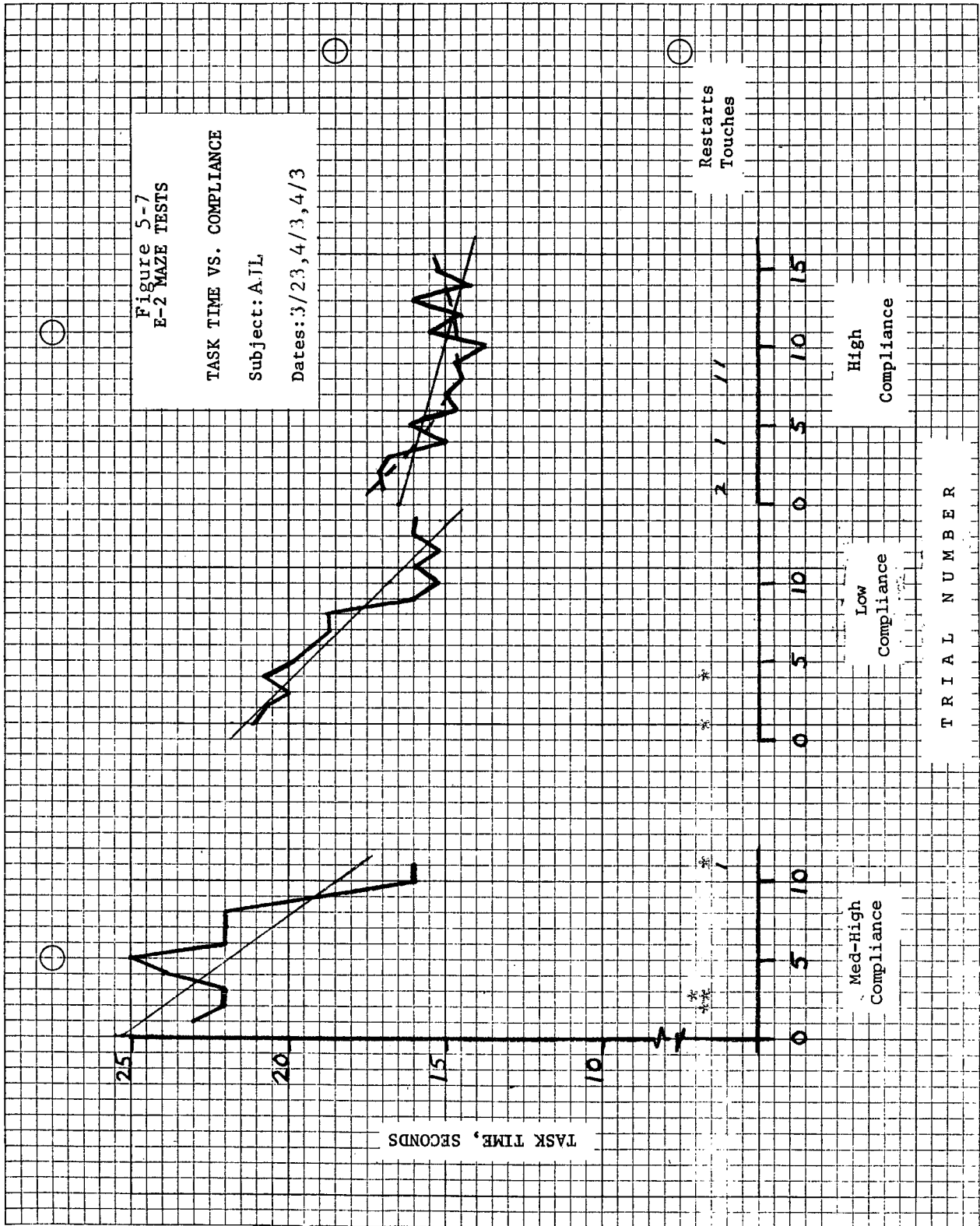Subject: RBD

Dates: 3/23, 3/29/3/31

Figure 5-6
E-2 MAZE TESTS

TASK TIME VS. COMPLIANCE

Subject: LEL

Dates: 3/23, 3/24, 3/31

TASK TIME, SECONDS

20

15

10

Med-High
Compliance

Low
Compliance

High
Compliance

Restarts
Touches

T R I A L   N U M B E R

35

Figure 5-7
E-2 MAZE TESTS

TASK TIME VS. COMPLIANCE

Subject: A.IL
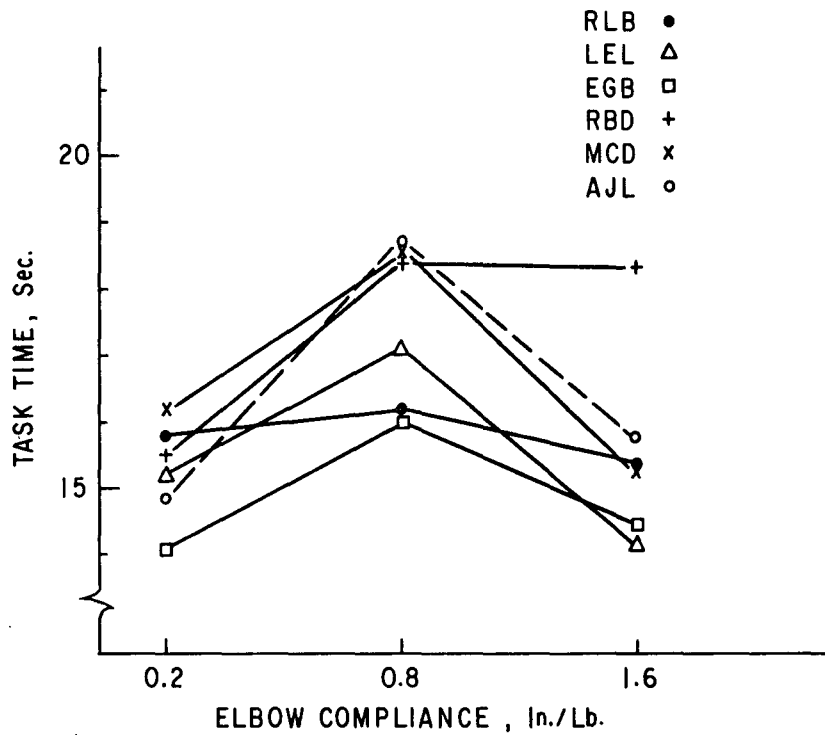
Dates: 3/23, 4/3, 4/3, 4/3

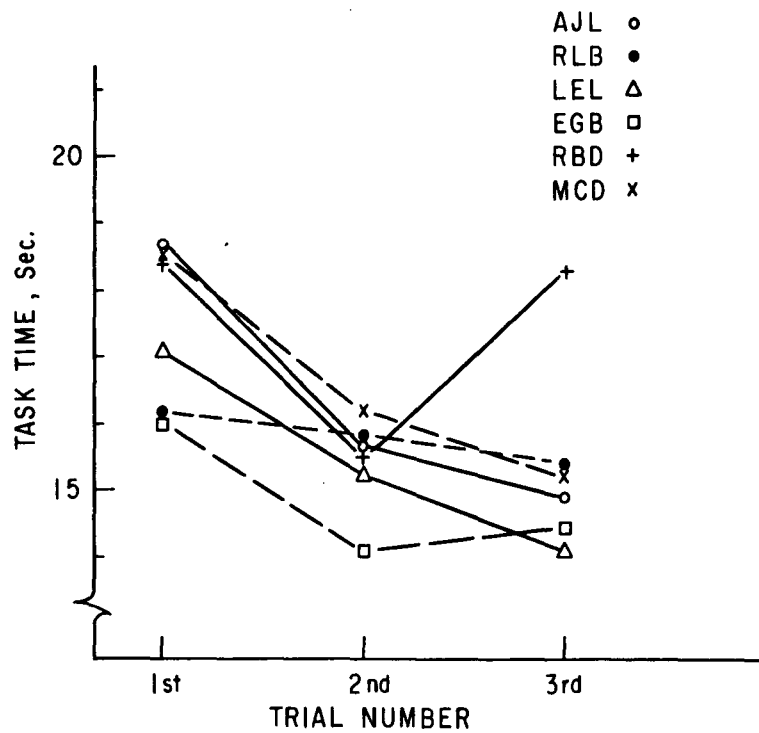Figure 5-8. Mean Task Time vs Compliance.

Figure 5-9. Mean Task Times in Chronological Order.

SECTION 6

SIMULATION OF E-2 AS TERMINAL DEVICE

6.1 Objective:

Assess the advantages and problems associated with a master/slave man-equivalent manipulator mounted on a long manipulator boom. The usefulness will be evaluated in three types of tasks, i.e., docking or assembly, inspection, and repair/refurbishment. Also, various video camera positions will be evaluated.

6.2 Description:

The E-2 slave six degree of freedom manipulator was hung on the end of the CAM 1400. Part of the original end effector of the CAM 1400 was removed and the counterbalancing adjusted as far as possible to balance the boom. The E-2 master was mounted on a mobile platform and nominally mounted just behind the CAM 1400 master station as shown in Figure 6-1. This allowed a single operator to run both the CAM 1400 (with right hand) and the E-2 (with left hand). Other arrangements were also tried, such as two man operations. Since the E-2 and CAM 1400 were not designed for the compatibility, part of the simulation was to evaluate the problems involved if for no other reason than to know what to avoid in future designs.

The purpose was more to qualitatively assess the concept rather than gather quantitative data, since there is really nothing to compare the concept with. Thus, a broad spectrum of possible uses and arrangements were investigated. A 3 x 3 design was used in which three different types of tasks were attempted with three different video camera positions. The three tasks are described as follows:

Task A – Aid in Docking or Assembly: The small NIMBUS style satellite mockup (see Figure 6-2) was pulled across the air bearing at a constant velocity. Different trials used selected velocities of either 0.1 or 0.3 fps. The boom started on the left and rotated slowly to the right and attempted to acquire the satellite, track it long enough

to determine its trajectory and an appropriate grab point. Then the operator reached out with the E-2 to grab the satellite, bringing it to rest.

Task B - Inspection: The same satellite from Task A was used, as well as the same velocities. However, inspection was done mainly with the satellite at rest. First, a nameplate with a series of numbers or letters was read; secondly, the Cannon electrical connector was inspected (two screws and proper seating); and thirdly, a micro-metroid impact point (simulated by a 1/2 inch black spot) was detected.

Task C - Repair/Refurbishment: The large nose cone adapter satellite was used here (see Fig. 6-3). The satellite was stationary except for two gimbaled motions. The steps in the task included removing a metal cover, attaching it to its Velcro tether point, peeling back the insulating blanket, reaching in and turning a valve, and then the reverse steps.

6.3 Procedure:

For Tasks A and B a device to pull the small satellite across the air-bearing floor at constant velocity was rigged. A fishing reel driven by a small d-c motor was used. The background of the air-bearing floor area was blacked out using black plastic film so that visual cues from the background were minimal. Lighting was from the ceiling fixtures.

The television system included two zoom cameras on remote control pan and tilt mechanisms. These cameras had about 600 line resolution. The position of the camera is shown in Figure 6-1. A miniature camera was also used for the inspection, it being light enough to be mounted on the E-2 arm or held in the E-2 jaw. A large studio quality camera was the fourth and final camera used for the 90° views.

The subjects were given verbal instructions including as much background information as needed to establish the objectives of the simulation. Since their best judgment was desired and their ideas for improvement were solicited, they were made to feel that their judgment was respected.

The times to record each phase of the simulation was recorded although carefulness was stressed in the instructions. We did not wish the work to be

done as quickly as possible if it was at the expense of collisions or other damaging possibilities. Times were mainly used for the subject's benefit, i.e., so they could tell how they were doing relative to previous runs and to other subjects.

The subjects were qualified to evaluate the system, its difficulties, advantages, etc. and extrapolate the concepts to design better matched to the shuttle manipulator boom. They were mainly engineers working in or familiar with the shuttle manipulator program. Also, one astronaut spent over an hour on the simulation.

Two debriefings were held in which the subjects discussed their likes and dislikes, any difficulties, or outstanding impressions they might have. These were held after the second day's trials on docking, and after the end of the simulation in task A and B. Also, many of the test runs were recorded on video tape. Only a single view at one time was recorded and this view was usually one of the views the subject saw.

6.4 Results & Conclusions

For the main part the results are documented by the video tape of selected runs and by the two debriefing sessions, (which have been transcribed from the audio tape). However, not all the gross errors are detectable when viewing the video tapes. Only one camera at a time was recorded, and for example - if the close up camera was being recorded, it might not show the end of the boom contacting or nearly contacting the solar panel of the small satellite in a docking sequence. However, an interested investigator would be able to tell what the cameras saw and establish the limitations of each view as well as getting a feel for the simulations.

The debriefings also lack any definite and concisive results or conclusions except for the unanimous consensus that ... "we really don't have enough trials

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on them (the E-2 and CAM 1400) to be able to say anything for sure". In both debriefings the fact that we were high up on the learning curve was brought out as well as the fictitiousness of the set-ups.

The discussion brought up the following topics, which I will try to summarize in an unbiased manner:

1. CAM 1400 Force Bias: The hose drag in azimuth was bothersome to most operators if not adjusted to minimal levels, especially when first running the machine.

2. E-2 vs. CAM 1400 Position Sensitivity: Since the E-2 moves one inch and the CAM 1400 over 10 inches for each inch of their respective master motion, the right arm controlling the CAM 1400 seemed much more sensitive than the left hand which controlled the E-2. Some operators mastered the co-ordination problem to a much greater extent than others. It was noted that most operators used but a very small portion of the E-2 working volume, preferring to move the CAM 1400 instead. This is attributed partly to the sensitivity problem but also is affected by the uncomfortableness of reaching extreme E-2 master positions while maintaining the control of the CAM 1400 with the right arm. To the latter point, some operators were mentally concerned about reaching out too far with the E-2 master and thus hitting the TV consoles. The consoles were always placed so it was possible to touch them, nevertheless most operators stayed a foot or more away.

3. TV Camera Positions: Some operators preferred the overall view camera mounted on the forearm while others preferred it at the base of the CAM 1400. Both had logical reasons for their preference as well as some intuitive feelings. All agreed that the 90° position was not very useful and few operators used this view even briefly when available. Also, there were differences of opinion on the location of the close up camera; some preferring the view to be looking at the finger tips of the E-2 and beyond, while others preferred to see the whole hand

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in view. It was almost universally agreed that two camera views on two monitors were about all the operator could use.

4. Depth Perception: Using only mono cameras, all had problems with depth perception. The strong tendency was to come up short of objects with E-2 hand instead of over extending it.

5. Direct vs. Indirect Viewing: Some preferred the total TV viewing instead of total direct viewing. The distance from operator to the worksite (12 to 20 ft.) was such that fine depth perception was lost, affecting no doubt the lack of confidence of some operators for direct viewing.

6. One Versus Two Man Operation: A majority preferred to do the operations by themselves while a minority felt they could do the task better with one operator running the CAM 1400 and the other operator the E-2. The majority felt they could handle the co-ordination problem (and would solve it with practice) and make adjustments with either master better (faster) than they could communicate their desire to their partner; whereas the minority felt they could concentrate more on the E-2 tasks if they allowed the other operator to worry about such things as clearances or TV camera adjustments, etc.

7. E-2 and CAM 1400 Combination: Most felt the combination was not optimal for docking or inspection and a single seven degree of freedom master-slave boom-manipulator was envisioned as being preferable. No strong comments were given on the repair/maintenance task, however only the author has had any appreciable amount of previous task performance experience. The tasks used were set up for one-handed operation, admittedly however, having the E-2 mounted on a movable base presented problems to me of inadvertent E-2 motion caused by the base (CAM 1400) movement when operating alone. On the other hand it gave a much greater working volume. Having a strong right handed preference, I would have felt more confidence if the E-2 was operated by the right hand and the CAM 1400 by the left.

8. CAM 1400 Arm Rest: An arm rest was added to the master station and all approved of it even though it was not used all the time. This was needed partly because the boom was not perfectly balanced but mostly required due to effort required to hold the operators arm extended for long periods.
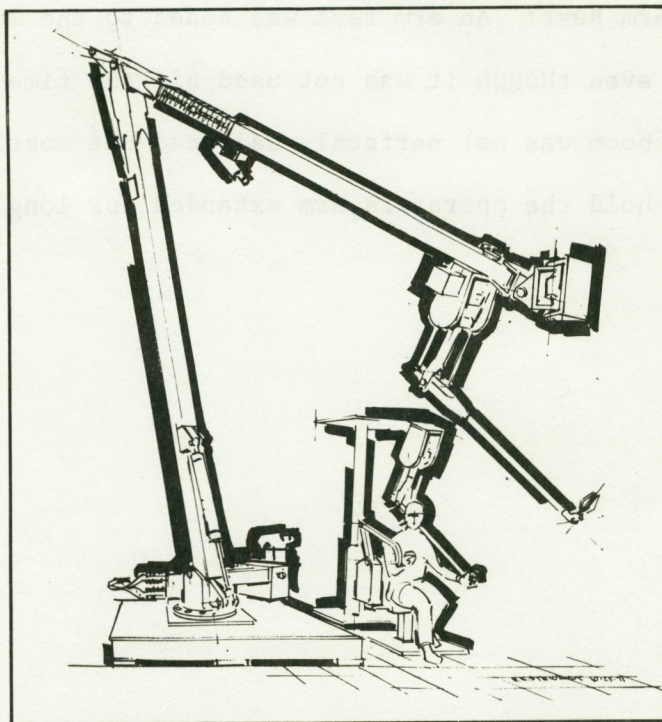
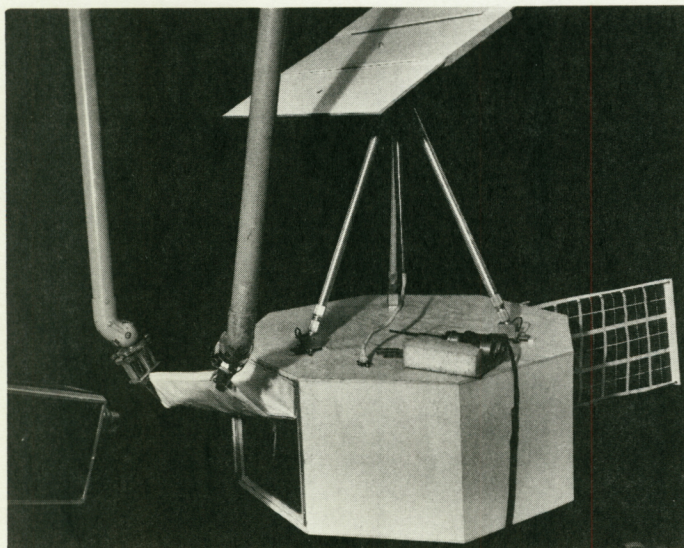Figure 6-1.   The E-2 Mounted as a Dextrous End Effector on the CAM-1400.

Figure 6-2. Small "NIMBUS" Style Satellite Used in Inspection and Docking Tasks. (Shown with E-2 Hands.)
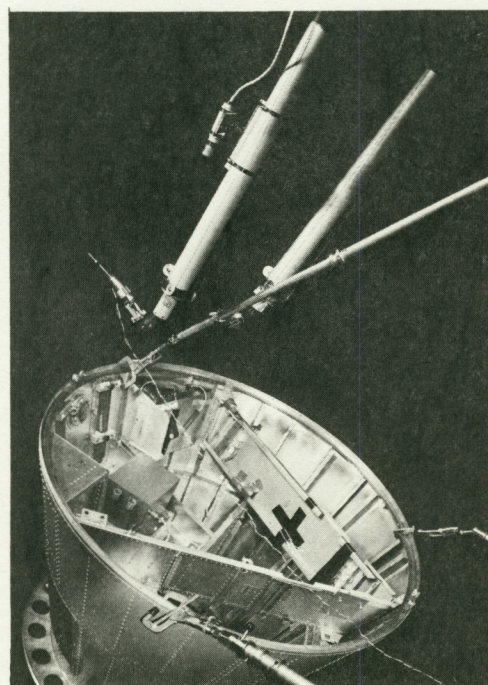

Figure 6-3.   Large Nose Cone Adapter Satellite Used in Repair/ Refurbishment Task.   (Shown Tethered and with M-8 Manipulator from Previous Simulation.)

EXPERIMENT III: CAM 1400 TASK PERFORMANCE

7.1 Objective:

To determine the effects on task performance when the parameter of manipulator compliance is varied and when the force feedback is removed from the master control. Task performance comparisons were made in a self-paced task wherein the CAM 1400 guided a large mass thru a two dimensional maze and also in a work paced task in which the boom caught and brought to rest the same mass which had been given an initial linear velocity.

7.2 Description of Apparatus and Procedure:

The air bearing floor and CAM 1400 have been previously described. The large mass consisted of a single rectangular piece of steel which weighed 7,000 lbs. The slab of steel was about 5 foot square by 6 inches thick. Since it was supported by four low profile airpads, the center of gravity of the system was about 6 inches from the floor. A vertical pole was bolted on the mass directly above the center of gravity. The aluminum pole was 2-1/2 inches in diameter and was about 24 inches high. The airpad-epoxy floor combination gave friction values less than 0.001 as the static frictional force level was measured to be a little less than 5 lbs. The drag of the trailing air hose probably contributed as much retarding force as friction at certain positions on the floor.

For the maze experiment, two 4 x 8 foot x 3/4 inch plywood sheets were used to inscribe the same pattern as used in the E-2 maze test but scaled up by 4 to 1. The maze was set over the mass with the pipe extending thru the 6 inch slot a distance of about 2 feet. It sat about 16 feet away from the azimuth rotation axis directly in front of the CAM 1400 slave. The master station was about 9 feet to the right of the slave (looking out at the maze from the slave), and to increase the operator's vision the whole master station was put upon a

30 inch table. Thus, the eye to maze angle was closer to that of the E-2 maze test, but was still not as good. That is, although the distance and objects were four times as large as the E-2 test, the clearances were not as discernable due to the slot being at a lower depressed angle. The E-2 angle of depression (the angle between the horizontal line and line of sight from the operator's eye to the horizontal slot) was 36° while in the CAM 1400 the angle was only 16°. Initially the sides of the maze had a touch sensing wire but after repeated runs this became a source of constant repair and was taken off. The experimenter subsequently counted touches by watching movements of the maze.

For the catching experiments, the same mass was used except that it was tethered to prevent it from moving off the floor. Initial velocity was obtained by one or two persons pushing on the mass for a few feet. Velocity was measured by timing the mass for a prescribed interval, usually 6 feet after the pushing stopped. The end effector used had two active pivoted fingers.

The procedure used for the maze test was similar to that of the E-2 maze test. All the subjects had previously completed the E-2 maze test, thus were familiar with the objectives and procedures. The tests were conducted over a 12 week timespan with most subjects having a 7 week break after completing approximately 50 to 70 runs. The experimenter kept track of the direction of the run (odd number runs started at the long circular arc), the task time, the number of errors (touches of the sides), and added comments such as "smooth" or "erratic". The points of contact were not recorded as they were in the E-2 maze test since it was observed in that test that the impact points were predictable from the direction being followed.

The compliance values were changed just twice for the maze test. The first 60 to 100 runs were run with the boom in a semi-low compliance. At the time it was thought that the azimuth motion was as low as the compliance could be set and yet remain a stable system. However, a pot wiring error was detected after

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the first set of runs which when connected allowed for increase in azimuth stiffness. The next set of runs were at a high compliance setting. The compliance was raised by lowering the gain in the servo loop, thus causing more slave deflection for the same force at the slave. The elbow, shoulder, and azimuth motion gain was varied such that the measured deflections were increased by about a factor of 3. This is, if the slave deflected 9 inches in azimuth under 60 lbs. load applied to the slave at low compliance, the deflection was about 27 inches at the high compliance setting. The master was clamped or grounded during these measurements. The original 9 inch deflection is made up of structural deflection and servo deflection of about equal parts. Thus, at the master the subject would have to put in about five times $(\frac{4.5}{27-4.5})$ the master motion to get the same force level at the slave in the high compliance mode as compared to the low compliance mode.

After 30 to 40 runs at the high compliance settings, 30 to 40 runs were made again at the low compliance setting to verify the learning curve and to see if there was any interference or transfer taking place. Remember that in this last set of runs the azimuth was at its full stiffness.

Finally, the force feedback was removed and the boom run in a unilateral mode. Relatively few runs were made in this mode due to reasons explained in the Results Section.

The procedure in the capture was to start the mass moving in a northerly direction on the south end of the floor, while the subject kept the boom in the northern half of the floor. Then when reaching a designated spot the operator was told to start; whereupon he moved the boom into position, tracked the mass and captured it if successful. The tests were run again in low compliance, high compliance and no force feedback modes.

Finally, movies were taken of the maze and capture tests in all three

modes. However, the movies will not show as dramatic effects since it was discovered that system hydraulic pressure had apparently dropped off during the first day of the movie sessions. It was not noticed until the force feedback runs were completed. Before the second day's movie runs, i.e., those without force feedback, the pressure was restored. The effect of lower system pressure is a slower responding boom and larger master slave desynchronization errors to get the same joint torque, which in effect lowers the system gain. Thus, the movies were at a higher compliance setting than those on the recorded data.

7.3 Results:

The data for the subjects is plotted in Figure 7-1 thru 7-7. Shown are the task completion times versus run number, i.e., learning curve data. Also, the data of tests, rest periods, compliance settings and number of errors is also recorded. Summarized in Figure 7-8 and 7-9 are all the odd numbered and even numbered runs respectively which had one or no errors. These figures then show the population learning curves with respect to times and errors. With more than one error, it is felt that some subjects might have "given up" on having a good run. One error was included to give more data points.

The learning curves in Figures 7-8 and 7-9 follow the expected trends, a steep initial curve for about 30 runs, followed by a flatter curve during the next 100 runs. The change in compliance shows up, but not too noticeably. The high compliance runs shown by cross's tend to be higher and with slightly more scatter, especially the initial runs at the higher compliance settings. Inspection of the individual curves show that the change in compliance affected some subjects more than others. For example, subjects EGB and MCD (Figures 7-2 and 7-5) shows a big jump initially and settling down to times not too different. Part of the jump may be due to the seven week lay-off, however, there is no data as yet to evaluate this possibility.

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To determine the effect quantitatively on task times with changes in
compliance, a comparison is made of five successful runs in each direction
or even number runs) in both compliance settings. To reduce the learning effect,
the last five successful runs of the high compliance mode are chosen, whereas
for low compliance, the five successful runs preceding the compliance change are
used. For two subjects, the change in compliance setting was done before 100
runs were completed and this made the preceding 5 successful runs extend well
back on the learning curve. Thus, for these two subjects, some low compliance
times are taken after the change back from high compliance. The results are
summarized in Table 7-1. Besides showing the small increase in task time due
to change in compliance, the greater effect of direction is evident from the
values in Table 7-1. It took about 1-1/2 seconds longer to run in the odd number
direction.

TABLE 7-1. Mean Times of Five Selected Runs

	Odd No. Runs		Even No. Runs	
Compliance	Low	High	Low	High
Subject				
RLB	16.14	16.98	17.90	16.52
EGB	15.18	15.78	14.02	14.34
CC	19.52	19.82	16.46	18.24
MCD	19.34	19.84	17.80	18.58
RBD	17.12	19.08	16.12	18.48
LEL	19.52	19.22	16.64	16.44
AJL	18.52	18.66	17.30	18.02
AVG.	17.91	18.46	16.61	17.23
Difference		+0.55 sec.		+0.62 sec.

This difference is reasonable since the even runs start at the portion of the maze with short runs and ends on the long sweep. Thus, starting from rest allows easier negotiation of the more difficult section and allows "pouring it on" in the final segment.

Returning to Figures 7-8 and 7-9, the learning of error free performance is seen by the density of points up to the 130 run point. Not all the subjects completed the full 170 runs and in Figure 7-8 is shown the number of subjects completing that particular number of runs. The density by looks alone can be deceiving because of the differences in time spreads. Therefore, in Figure 7-10 the density is shown as per cent of runs successful (1 or no errors) in each decade of run numbers. The even runs seem to be increasing in percent of successful runs whereas no trend is evident in the odd number runs. Both runs seem to bulge upward in the middle where both compliance settings have runs. One would then suspect that the high compliance had a better success ratio. Taking the total for both cases does show that result as shown in Table 7-2.

	EVEN RUNS		ODD RUNS	
Compliance	Low	High	Low	High
	45%	53%	39%	50%

TABLE 7-2. Percent Successful Runs

The maze test was seemingly impossible without force feedback. Of forty runs recorded to date and numerous practice runs, none were made without errors. Most runs had rather serious errors, displacing the maze several inches or even knocking it down. Of the recorded runs, the average number of errors was 9.5 while the run with lowest number of errors had three. The most successful operators were those who learned to use two hands on the master. The initial

problems were: 1) putting in small oscillations at the master that were magnified by the position ratio and 2) not keeping the master in a level plane which caused the boom to lift up on the mass or push down on it. If the latter signal becomes too large, the grip on the pipe was lost suddenly. The erratic motion caused by the first problem was due mainly to over-corrections by the subjects. The loss of grip problem was controlled after practice by most subjects, usually by observing the deflection of the end effector. The oscillations were controlled by learning to move slowly and carefully, hence the usefulness of two hands.

The results for the satellite capture test are summarized by bar charts shown in Figures 7-11 and 7-12. Figure 7-11 plots the number of successful and unsuccessful captures as a function of the velocity of the mass for the full force feedback case. Below 1.0 fps the successful capture ratio was 100%, between 1.0 and 2.0 fps the ratio was 69%, and between 2.0 and 2.8 fps the ratio was 80%. The last group, i.e., above 2.0 fps was done by only one subject (the author) who had a series of 25 consecutive runs. For the non-force feedback case, although the task was indeed possible, comparison of Figure 7-11 and 7-12 show the hindrance caused by the lack of feedback. Below 1.0 fps the success ratio is 53% and between 1.0 and 1.5 fps, the ratio is only 16%. Not shown by the numbers is the "quality" of the capture, i.e., did the boom catch the mass softly or was there an impact? The movies of the runs with and without force feedback show the expected results of better catches with force feedback.

It should be remembered that not only is it harder to track a higher velocity but that less time is available. For instance, at the 2.0 fps velocity the subject had only about 9 seconds to rotate the CAM 1400 in azimuth (about 50°), adjust the height of the end effector to that of the pipe, and then track and grab at the same time. It was necessary to track when closing the jaws of the grabber because of its slowness of closing. It took between 2 and 3 seconds for the jaws to close. Many of the unsuccessful runs were caused by the slow acting jaws.

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7.4 Conclusions:

It is apparent that the effect of higher compliance and removal of force feedback to the master is detrimental to this type of boom manipulator when performing these particular tasks. Although the higher compliance setting increased the task time by over 0.5 seconds, this is not statistically significantly greater at the 90% confidence level. Thus, the effect here of a 5 to 1 apparent compliance setting is small. But, nevertheless, it is felt that the effect of higher compliance is somewhat detrimental, even if not provable by statistical methods for the amount of data taken in this experiment. Not enough data was taken to show conclusively that the lack of force feedback was detrimental since it was evident that a good deal of learning was still going on. The subjects all strongly testify, however, to the much greater difficulty without force feedback. The fact that no subject has yet attained an error free maze run even when this is their only objective indicates the strong degradation of performance. Generally, the consensus is that without any feel, one must visually sense displacement, velocity, and acceleration to judge or predict the path, and then one must apply the appropriate signal quite correctly. Contrary-wise, with feedback, one felt the amount of force being applied and thus had an approximate acceleration level. Also, force feedback effectively prevents step or near step slave commands which means that the oscillations and overshoots from the desired path are effectively damped out.

In the maze task, the CAM 1400 manipulator was controlling a large mass at the subjects own pace. In the satellite capture task, only the mass of the boom was being controlled while the subject tried to follow and catch the moving mass. Although the effective mass was different, the results were similar in that the operator felt he had a boom that was too "hot" to handle in both situations without force feedback. One could conjecture that with greatly decreased force and inertia levels, the lack of force feedback would be more acceptable. This might

be so, but only if the master/slave position ratio was closer to unity. Other

disadvantages, such as power consumption and damage control, would remain but

these effects have not been studied by the work undertaken in this contract.
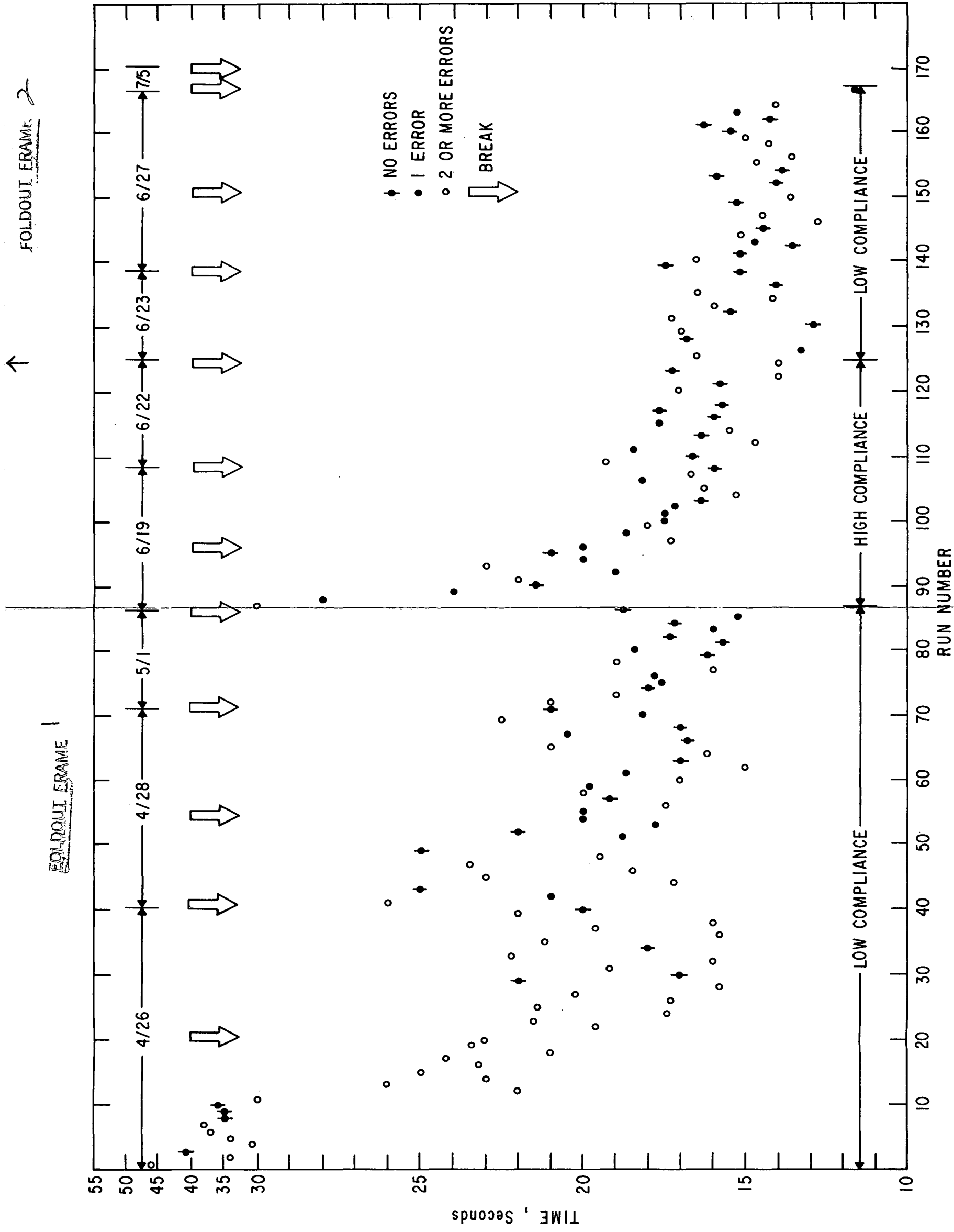
FOLDOUT FRAME 1

Legend:
- NO ERRORS
- 1 ERROR
- 2 OR MORE ERRORS
- BREAK

LOW COMPLIANCE HIGH COMPLIANCE LOW COMPLIANCE

TIME, Seconds

RUN NUMBER

Figure 7-1. Data for Subject RLB - CAM 1400 Maze Test.

54

FOLDOUT FRAME 1
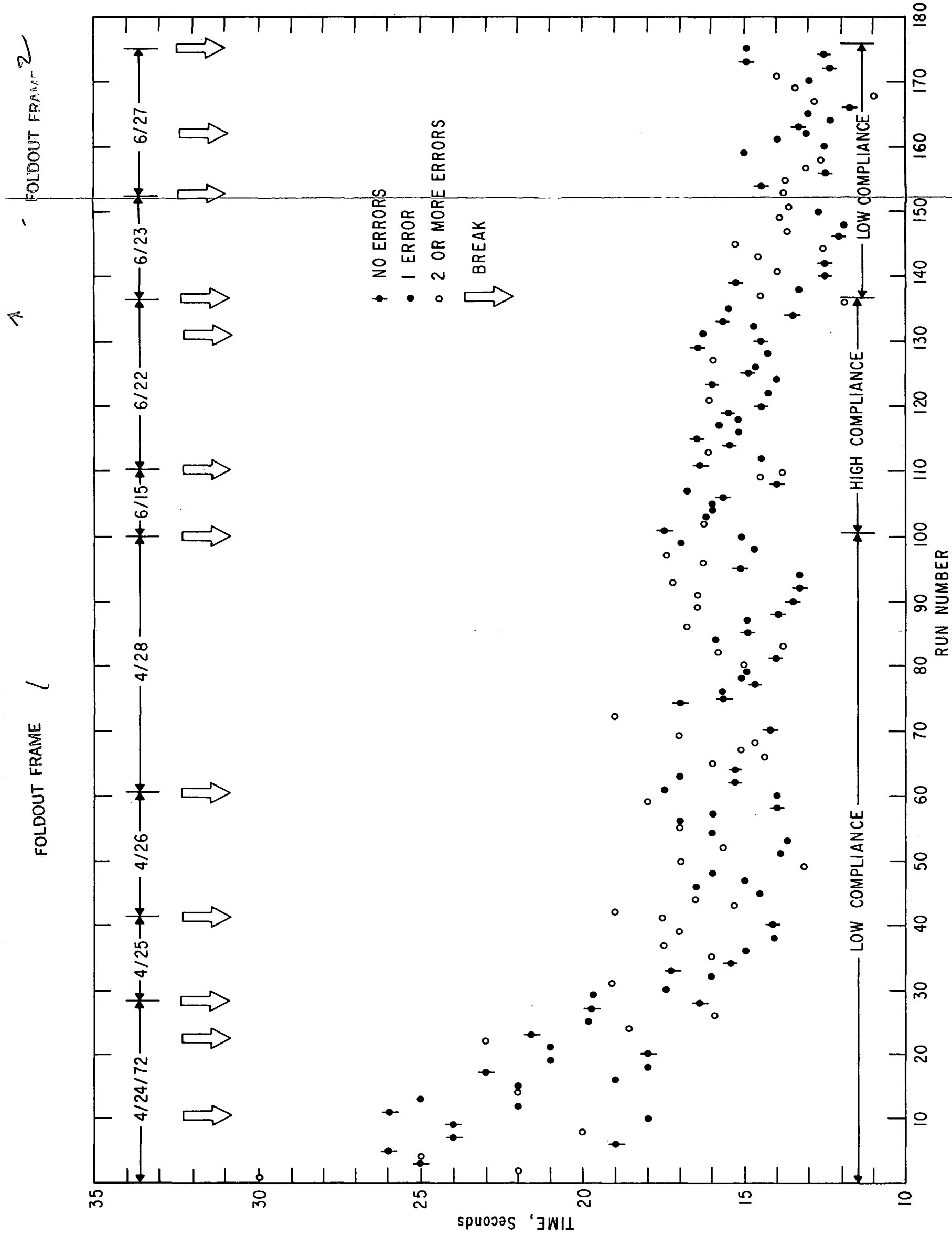
FOLDOUT FRAME 2

Figure 7-2. Data for Subject EGB - CAM 1400 Maze Test.
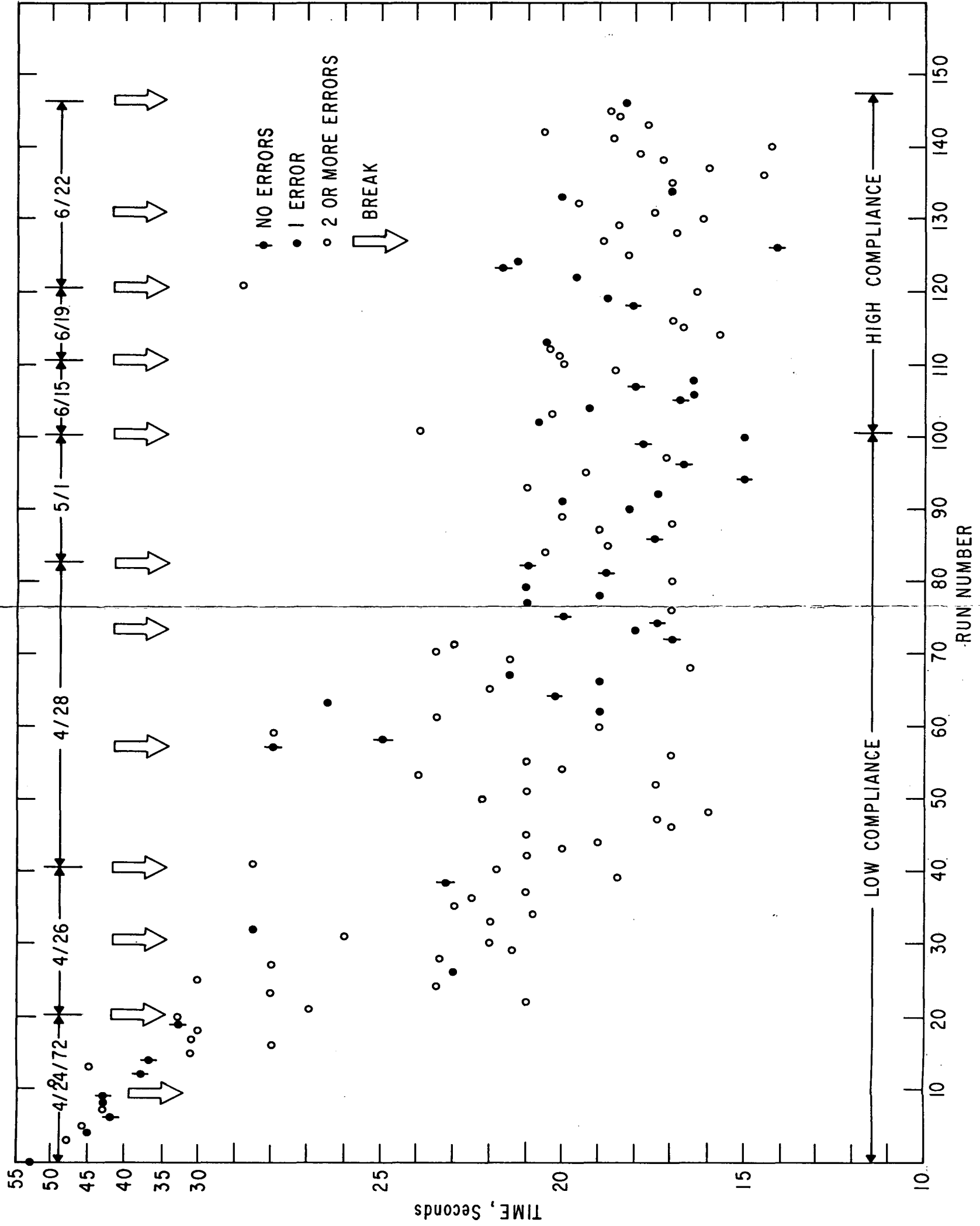
Figure 7-3. Data for Subject CC - CAM 1400 Maze Test.

56
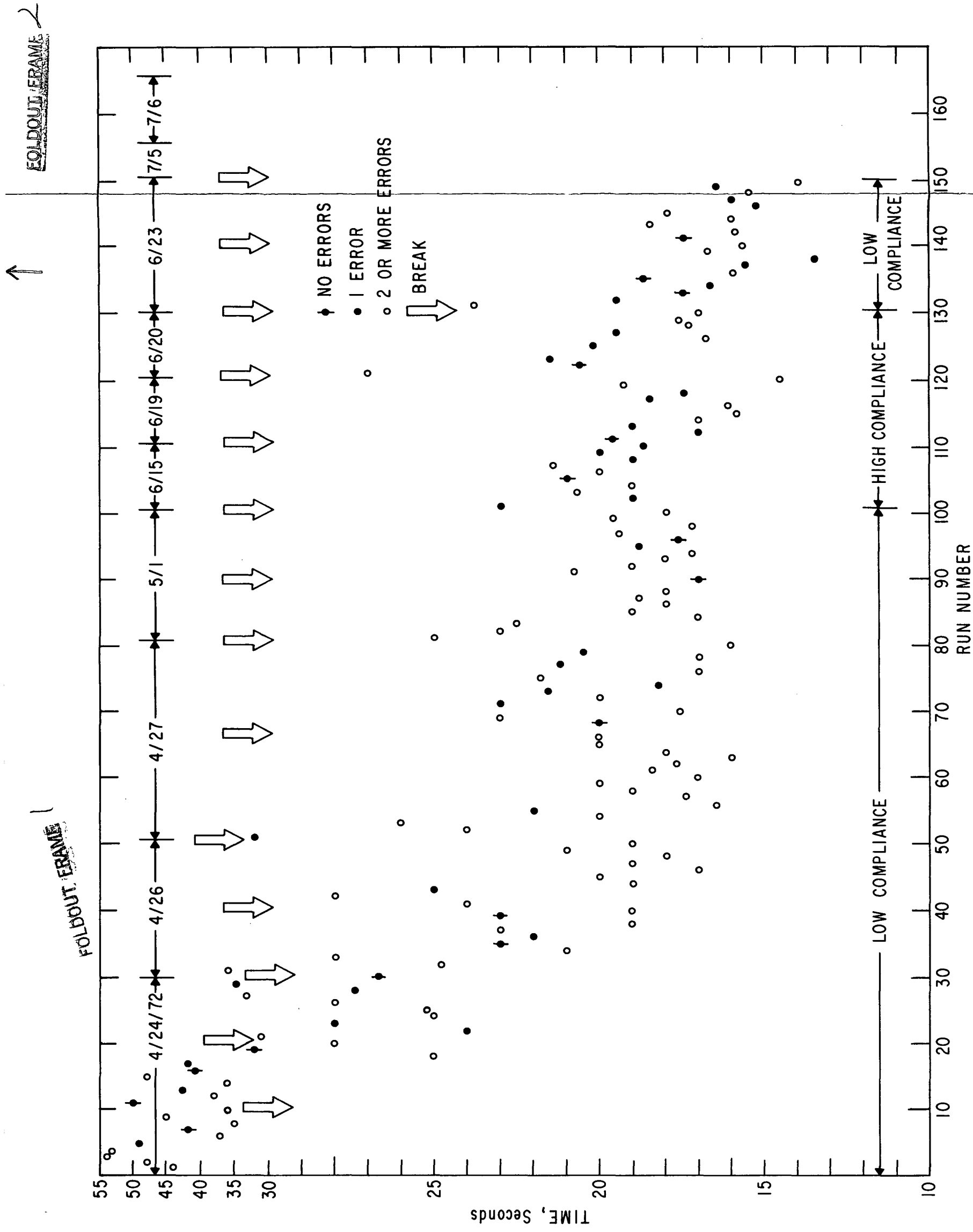
Figure 7-4. Data for Subject MCD - CAM 1400 Maze Test.
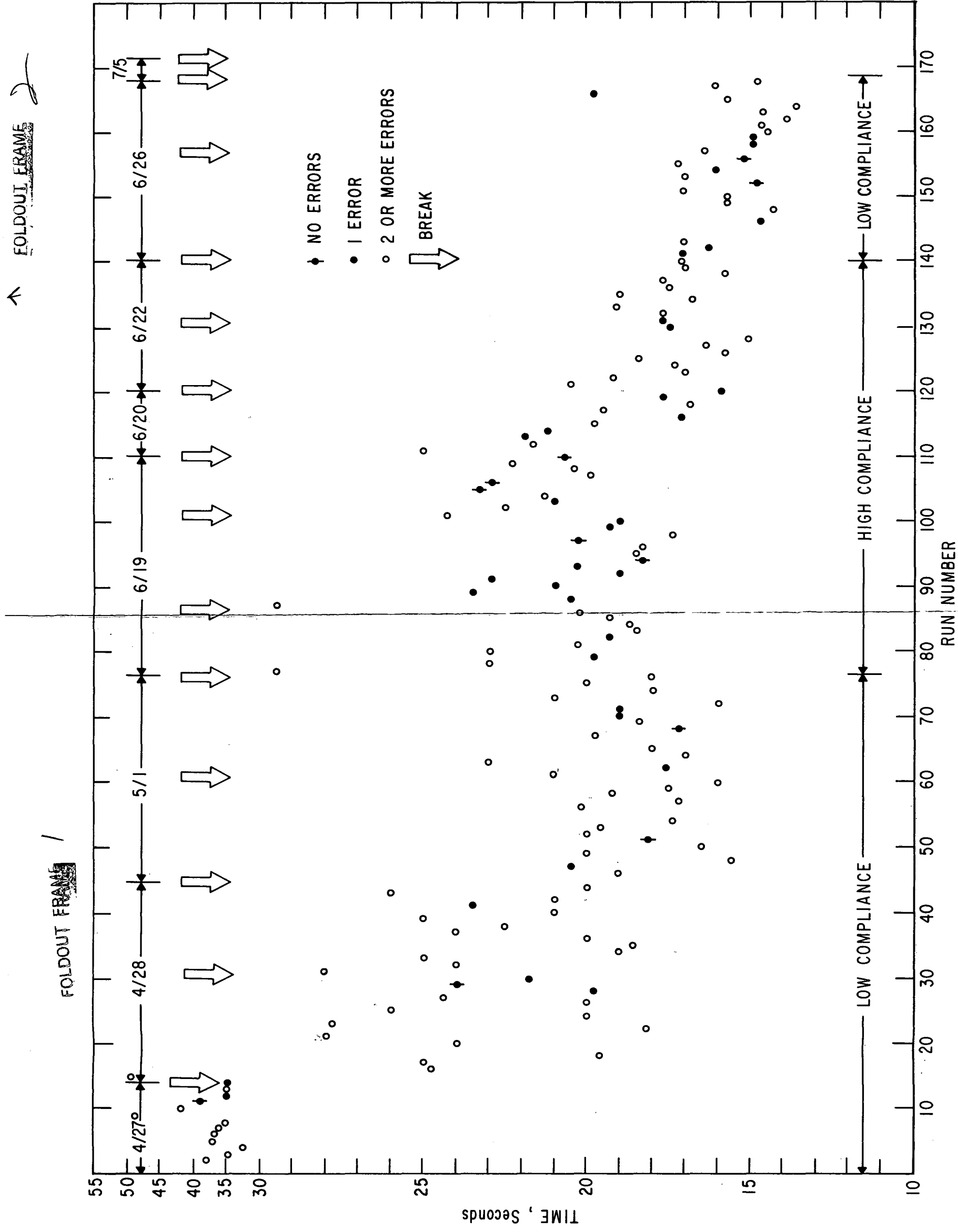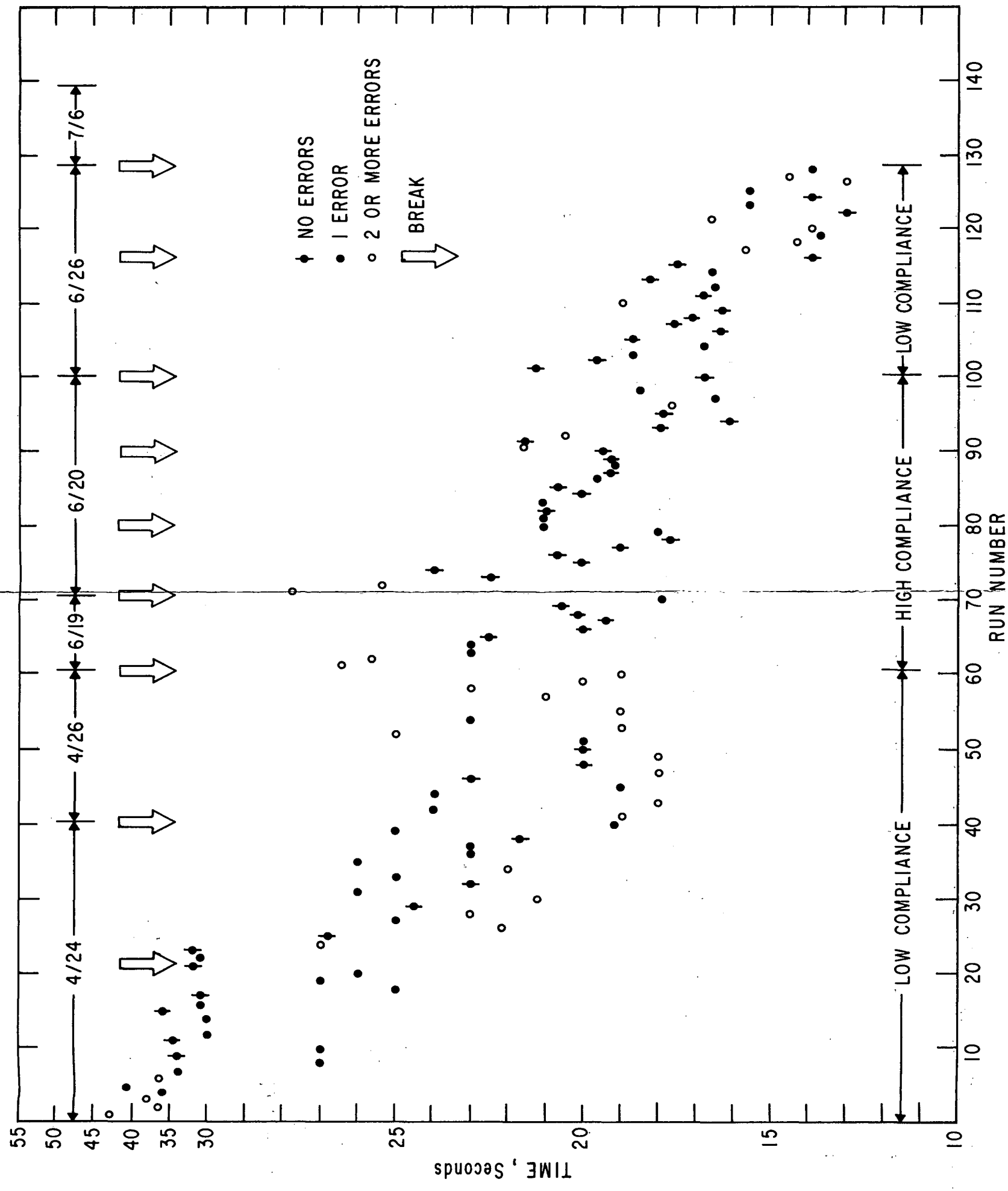
Figure 7-5. Data for Subject RBD – CAM 1400 Maze Test.

58
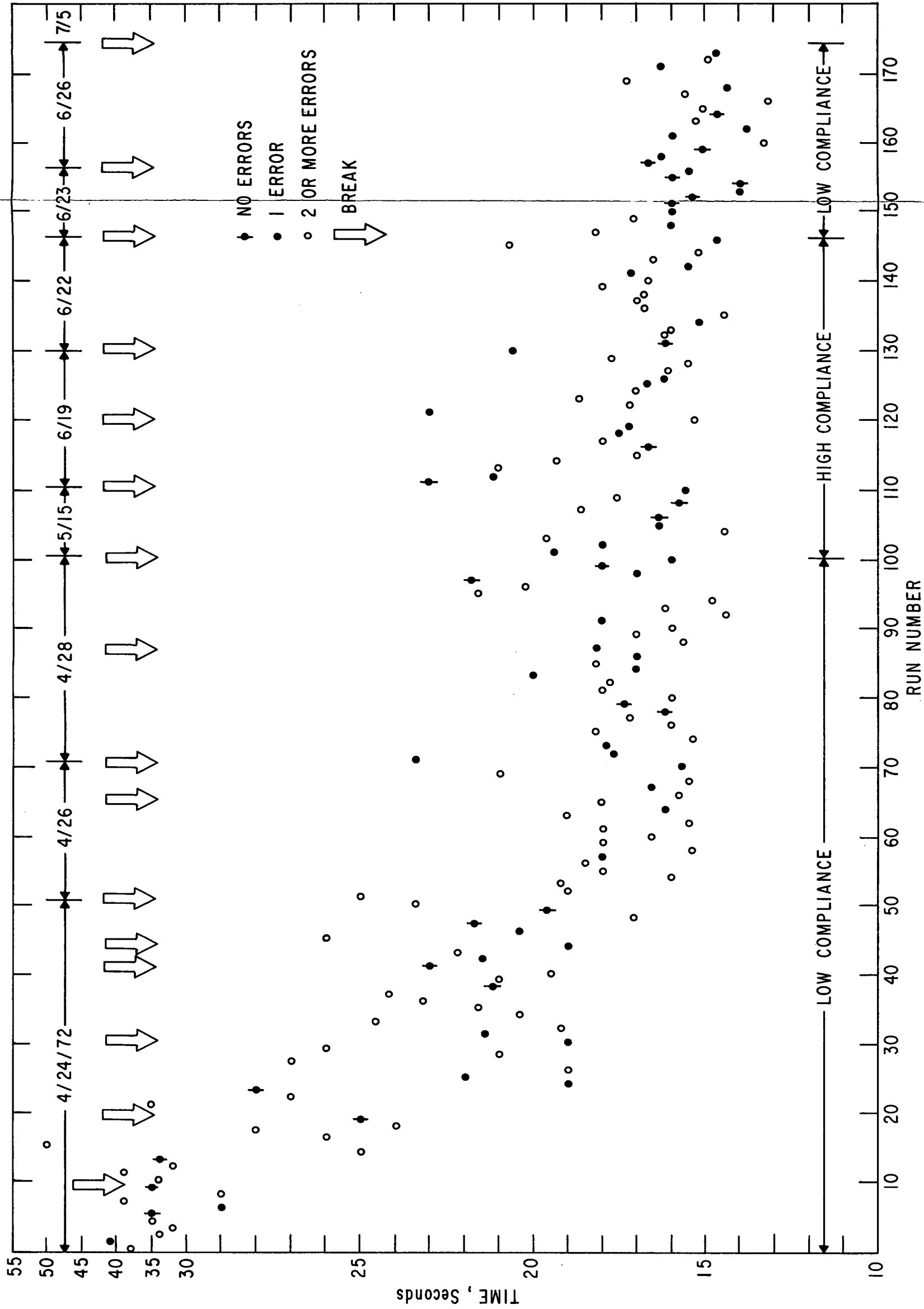
Figure 7-6. Data for Subject LEL – CAM 1400 Maze Test.
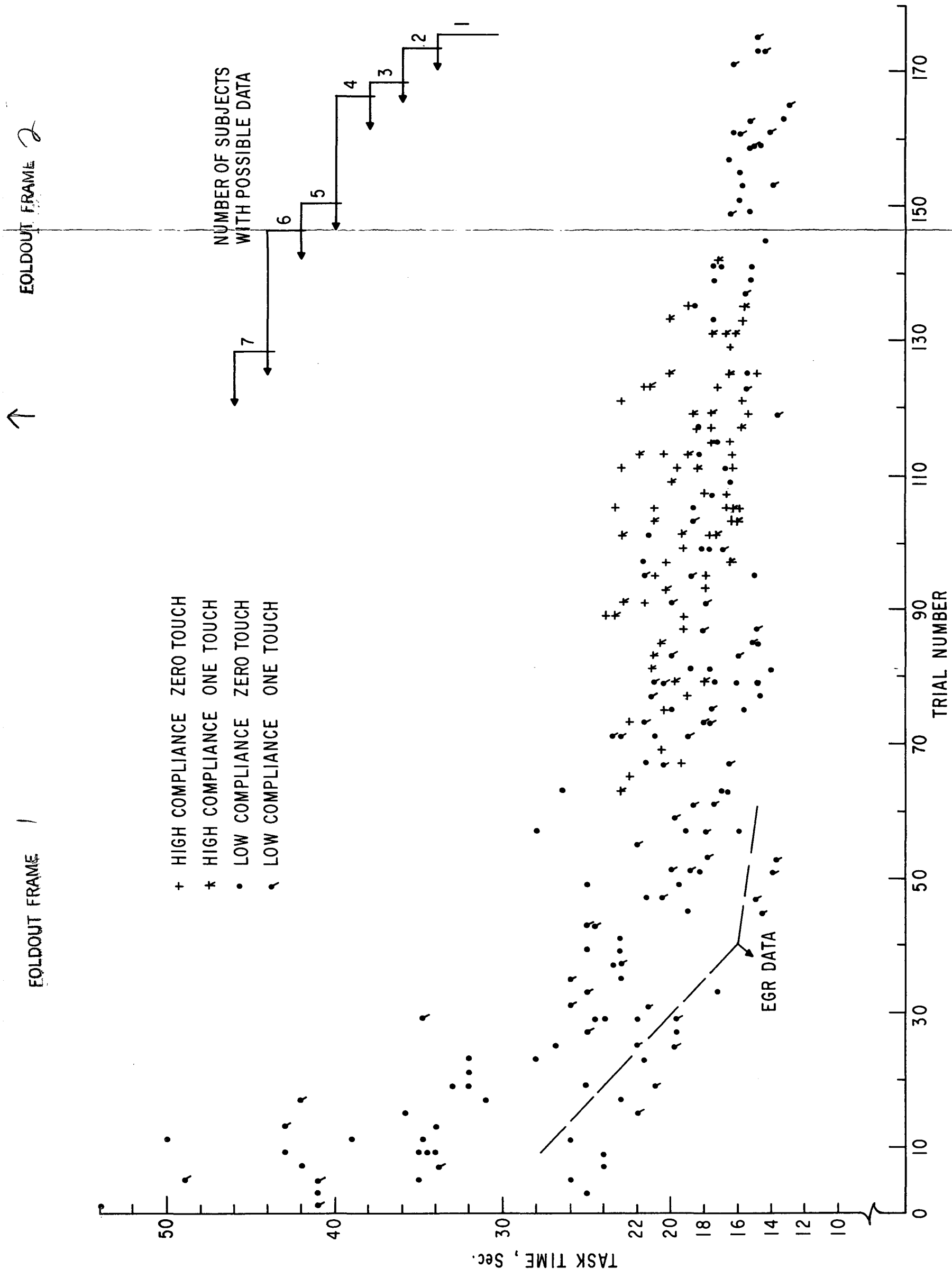
Figure 7-7. Data for Subject AJL - CAM 1400 Maze Test.

60

EOLDOUT FRAME 1

EOLDOUT FRAME 2

+ HIGH COMPLIANCE ZERO TOUCH
⋆ HIGH COMPLIANCE ONE TOUCH
• LOW COMPLIANCE ZERO TOUCH
↙ LOW COMPLIANCE ONE TOUCH

NUMBER OF SUBJECTS
WITH POSSIBLE DATA

EGR DATA

TASK TIME, Sec.

TRIAL NUMBER

Figure 7-8. Successful Odd Number Runs (i.e., Zero or One Touch) for All Subjects.
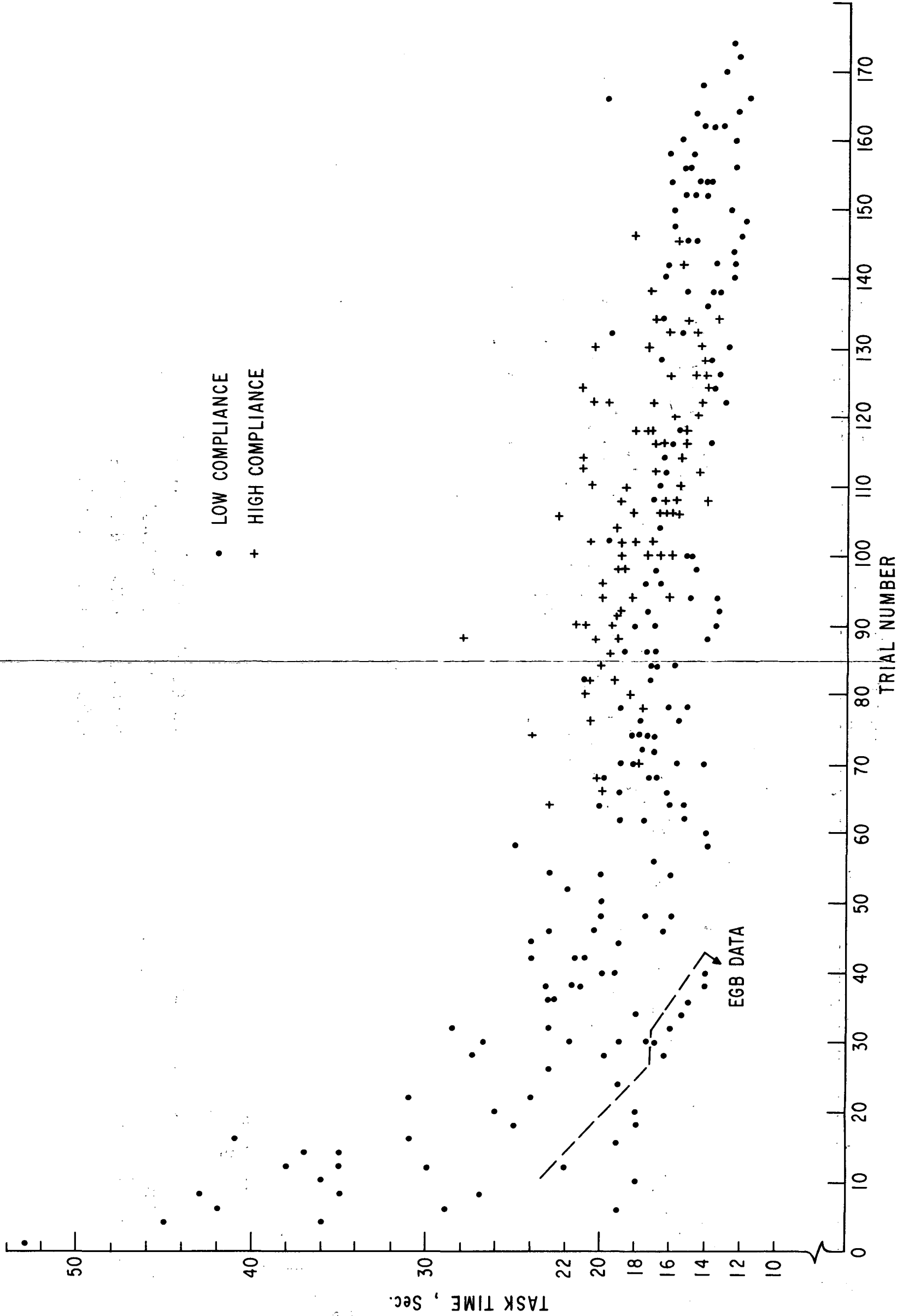
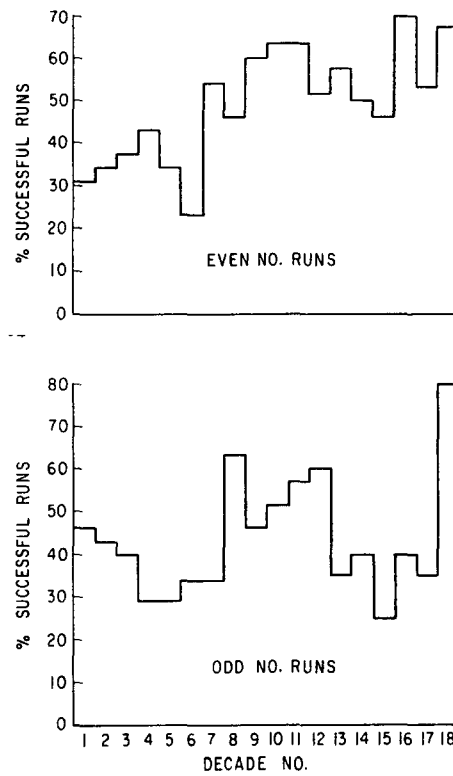Figure 7-9.　Successful Even Number Runs (i.e., Zero or One Touch) for All Subjects.

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Figure 7-10.   Percent Successful Runs As Learning Progressed.
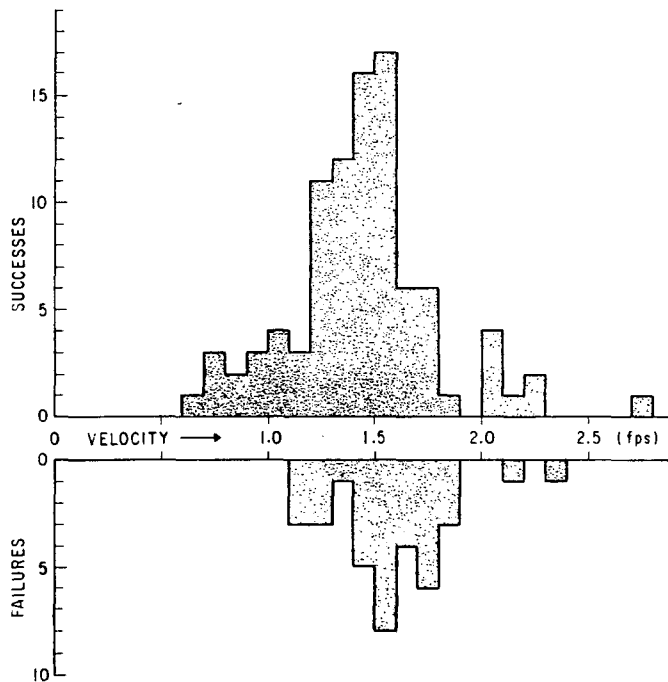

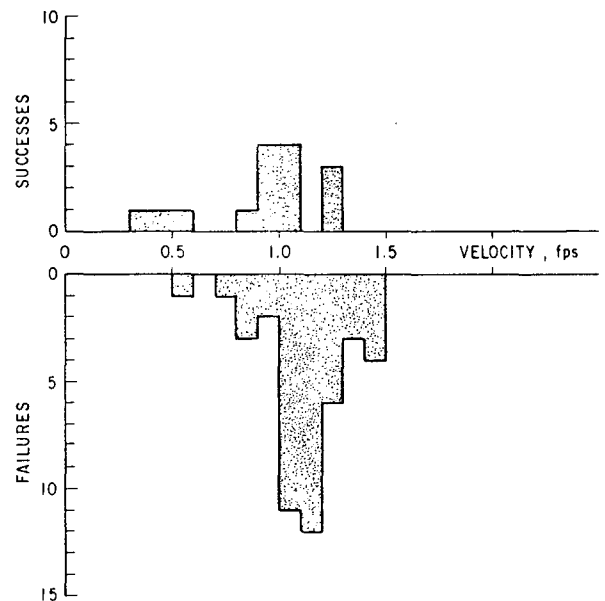Figure 7-11.   Satellite Capture Results
with Force Feedback.

Figure 7-12.   Satellite Capture Results
without Force Feedback.